Miras and, in particular, R Leo

Results from
theoretical calculations and
observations

Outline

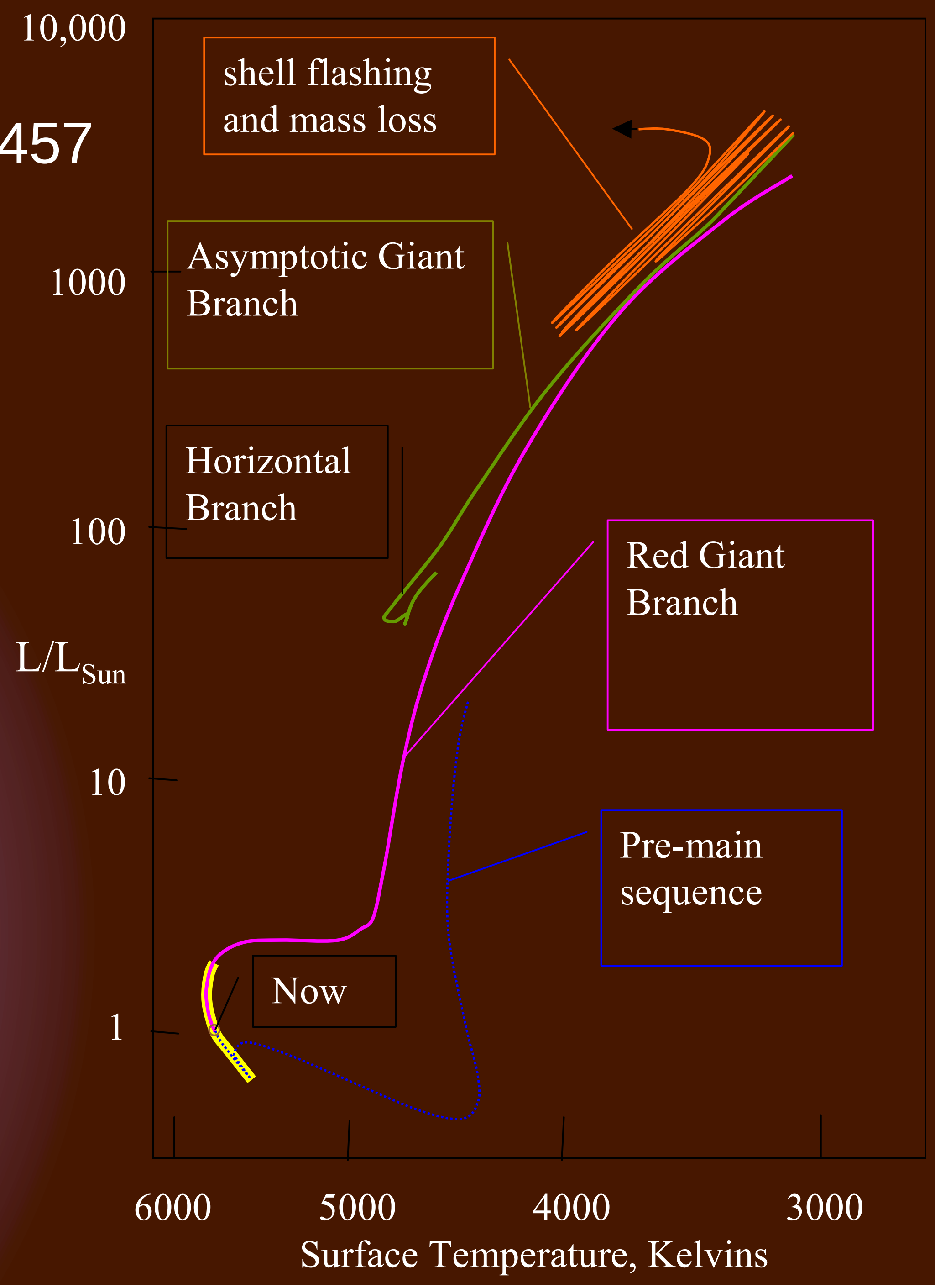
1. Miras in context.

2. Atmospheric structure and time-dependence

3. Departures from spherical symmetry

4. How big are these stars, anyway?

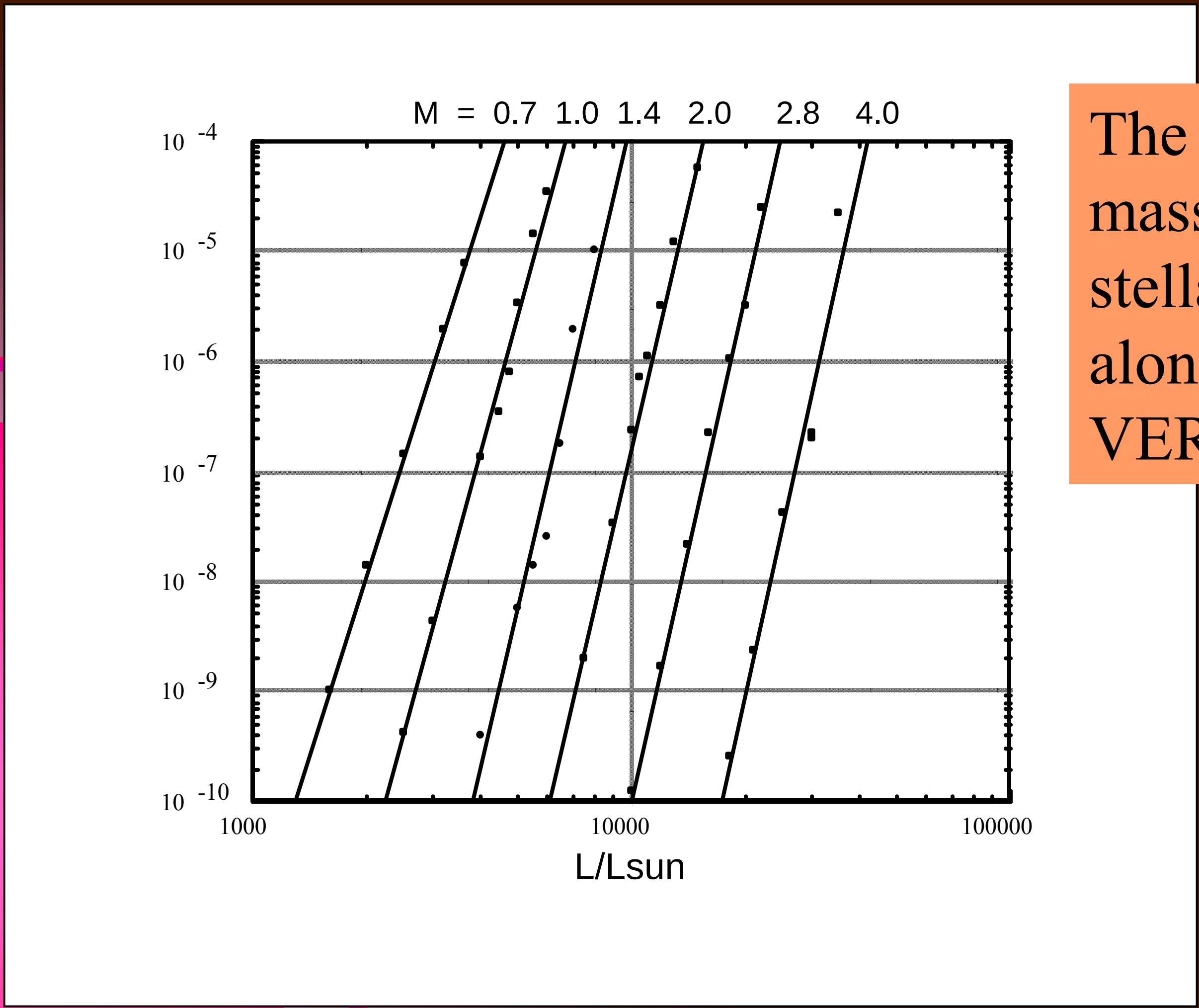
From Boothroyd, Sackmann, and Kramer 1993, Ap. J. 418, 457



Terminal AGB mass loss

- Often treated using Reimers' Relation (proportional to LR/M)
- Detailed models give very different results
- Fates of low-mass stars (0.8-8 M_{Sun}) depend on the mass loss law

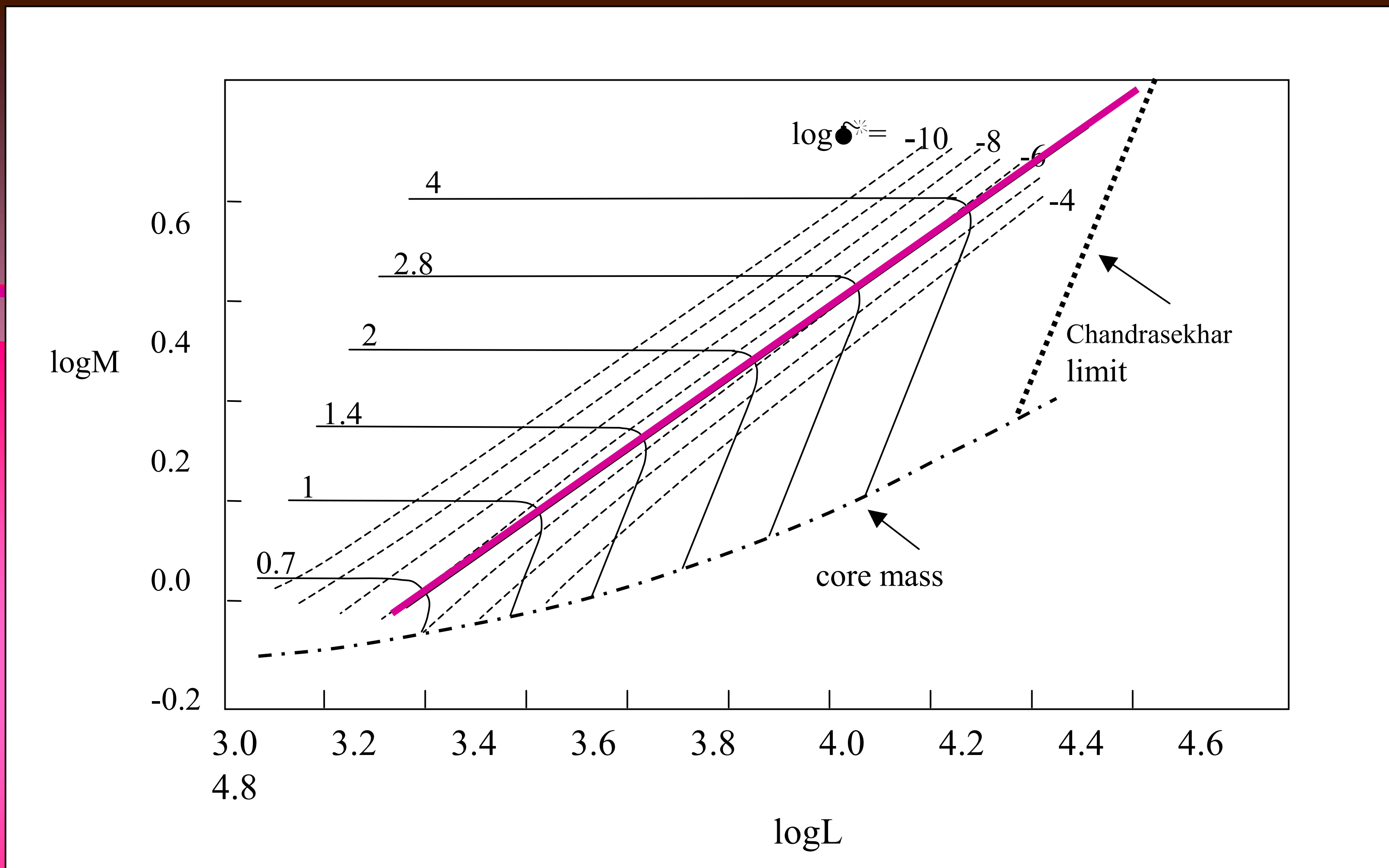
Models by Bowen (1995 grid) constraining evolution to follow reasonable tracks:



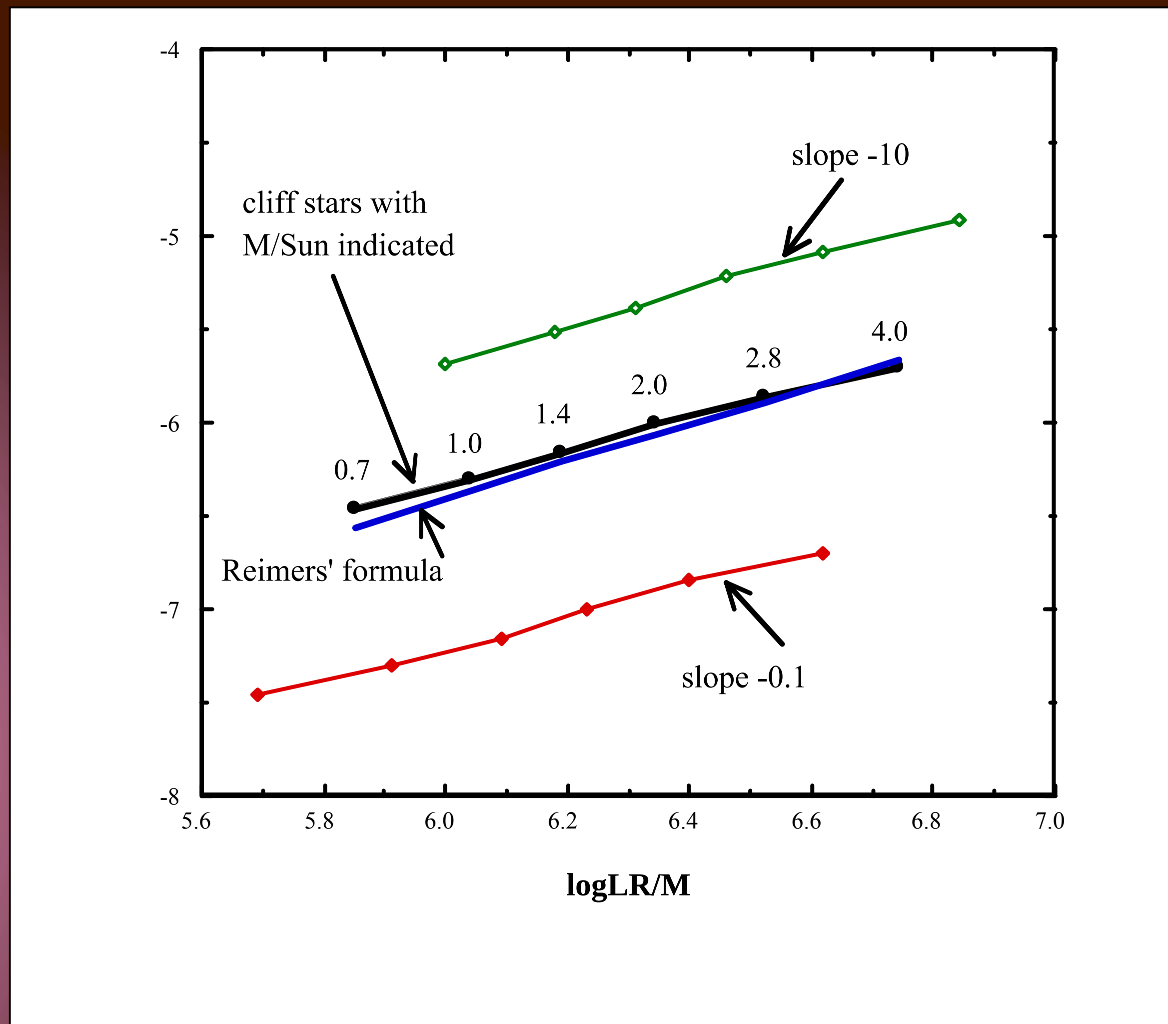
The dependence of mass loss rates on stellar parameters along the AGB is VERY steep.

Sources: see Willson 2000 In ARAA.

Stars evolving up the AGB lose little mass until they are close to "the cliff" where $t_{massloss} \sim t_{nuclear}$:

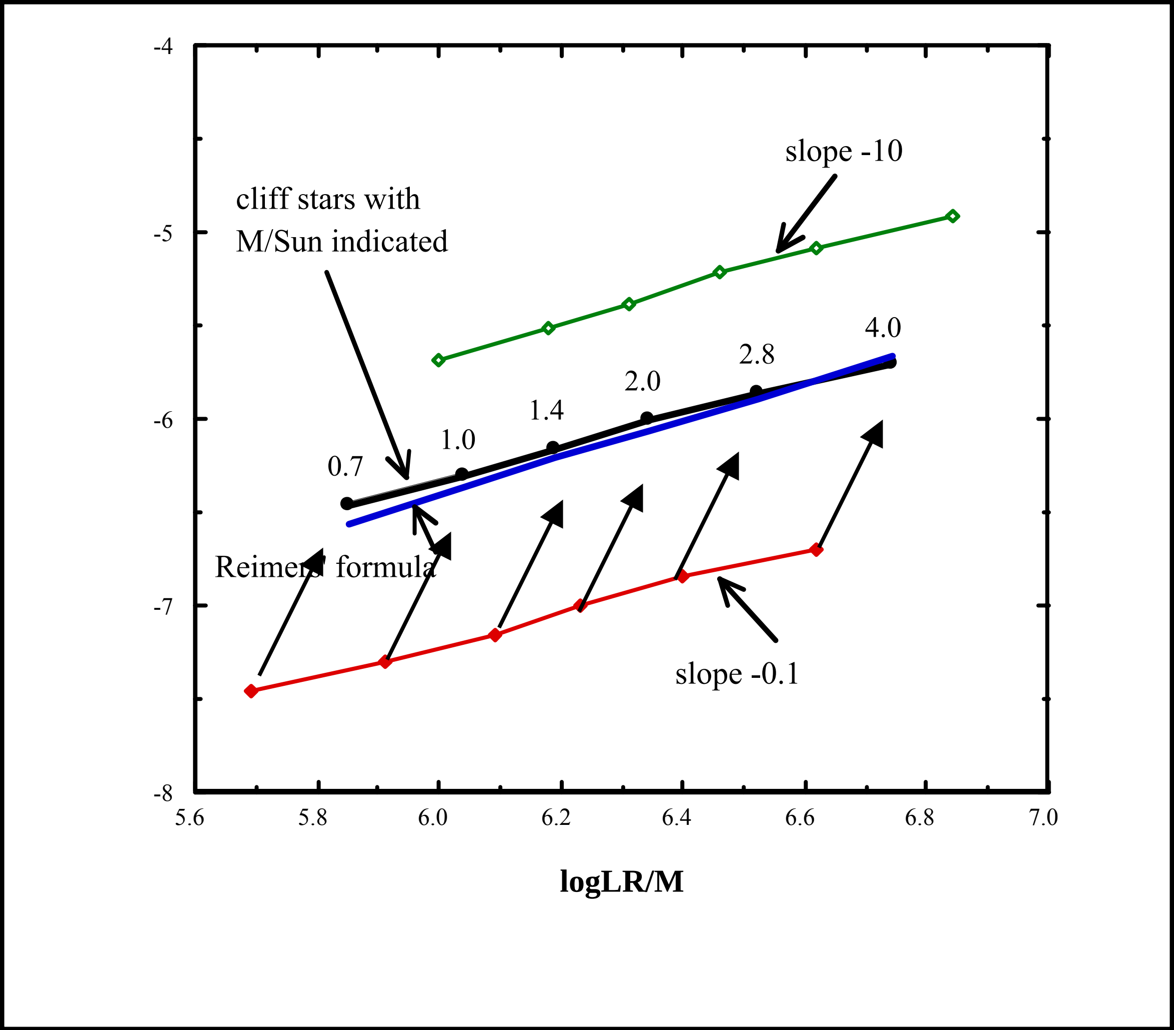


Empirical relations result from selection effects with very steep dependence of mass loss rates on stellar parameters.

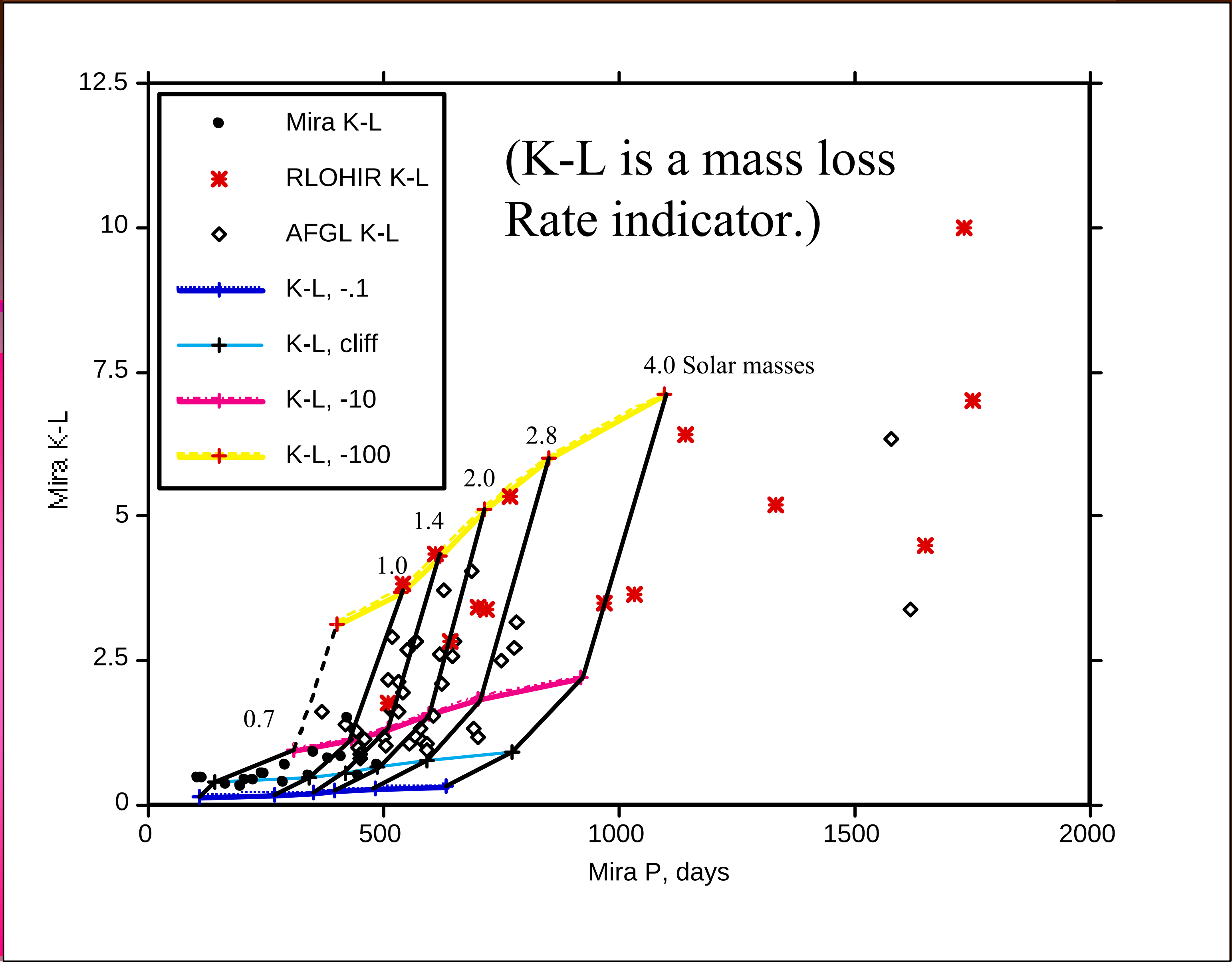


Individual stars do NOT follow Reimers' relation as they evolve.

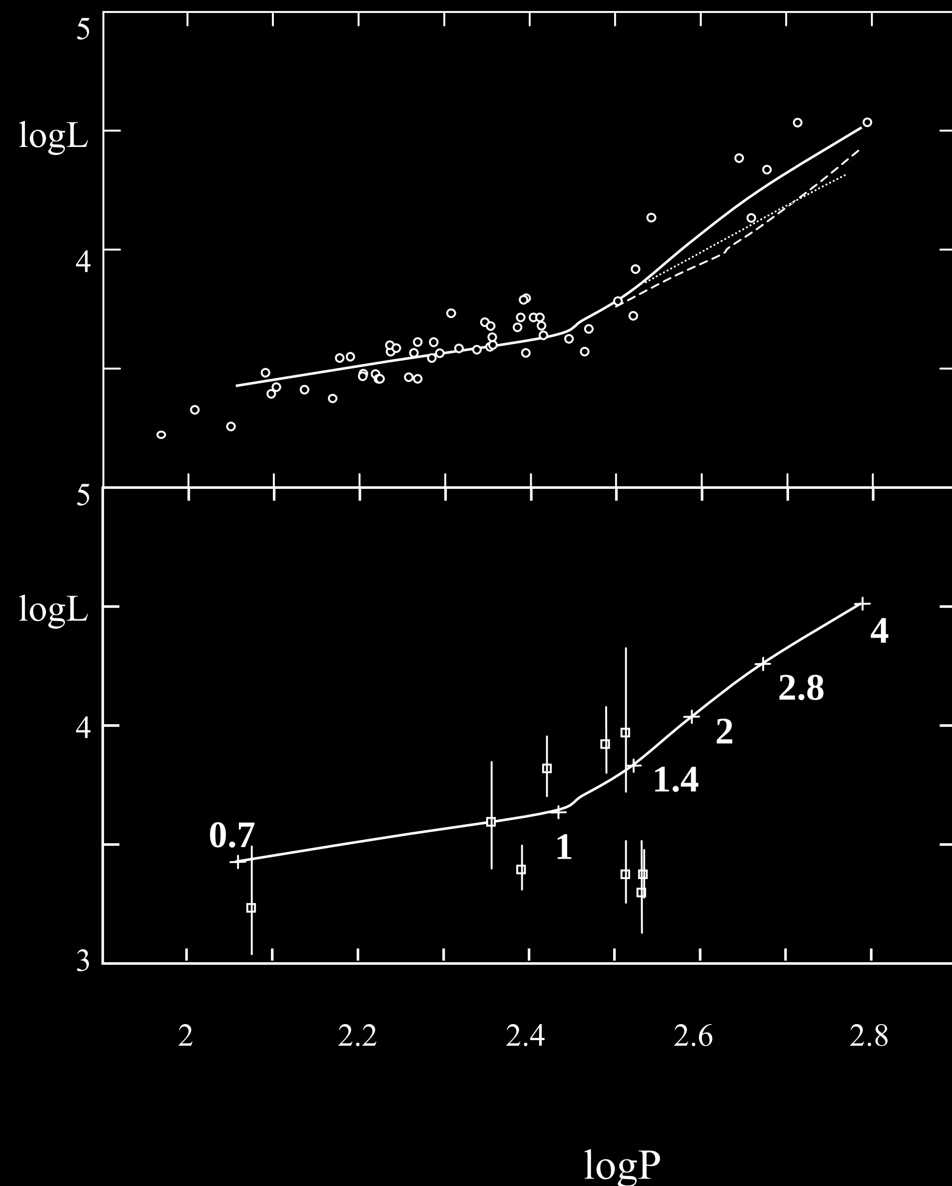
Reimers' relation is a kind of main-sequence for mass loss: It tells us which stars are losing mass, not how one star will lose mass



Observations of Miras and OH-IR stars confirm that Miras mark the location of the cliff:

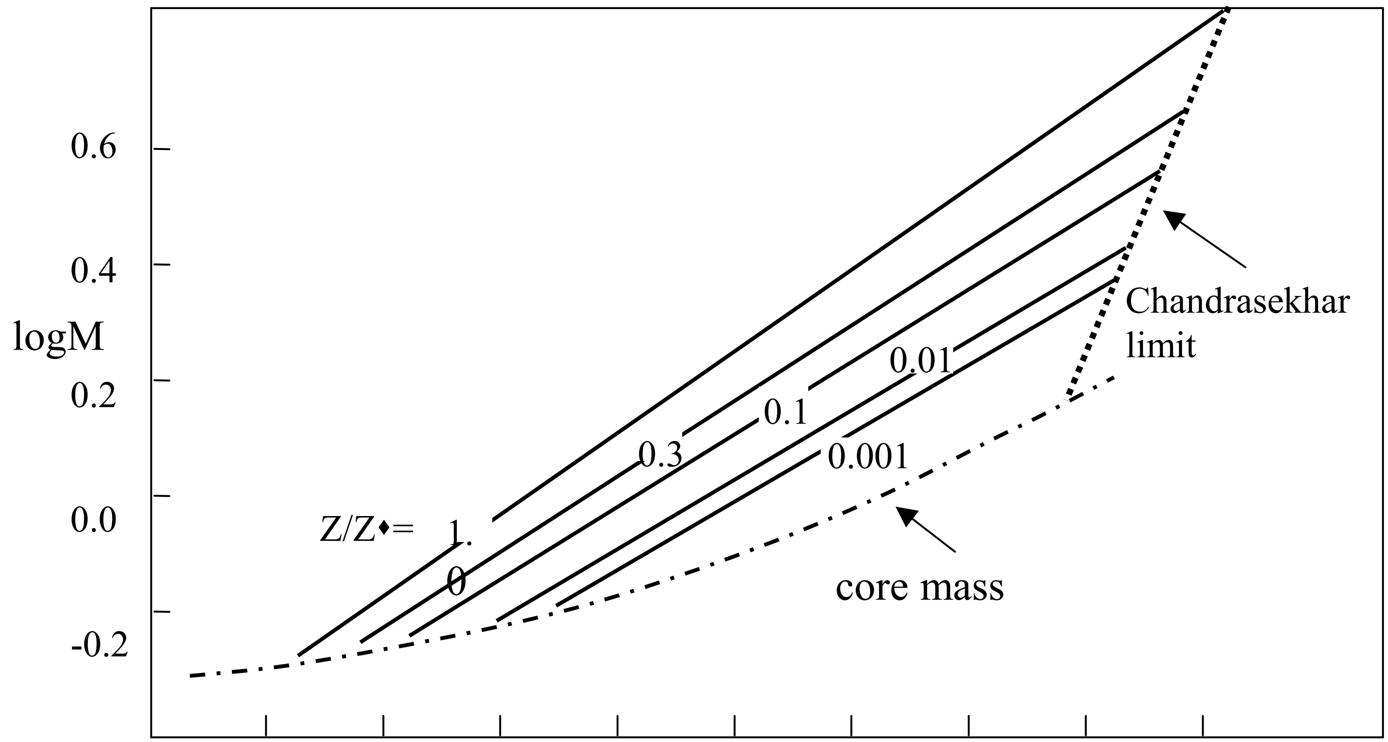


The cliff fits the observed Mira P-L relation from the LMC very well.



Hipparcos distances to Miras show a lot of scatter.

Now we can "predict" how different populations of stars will end:

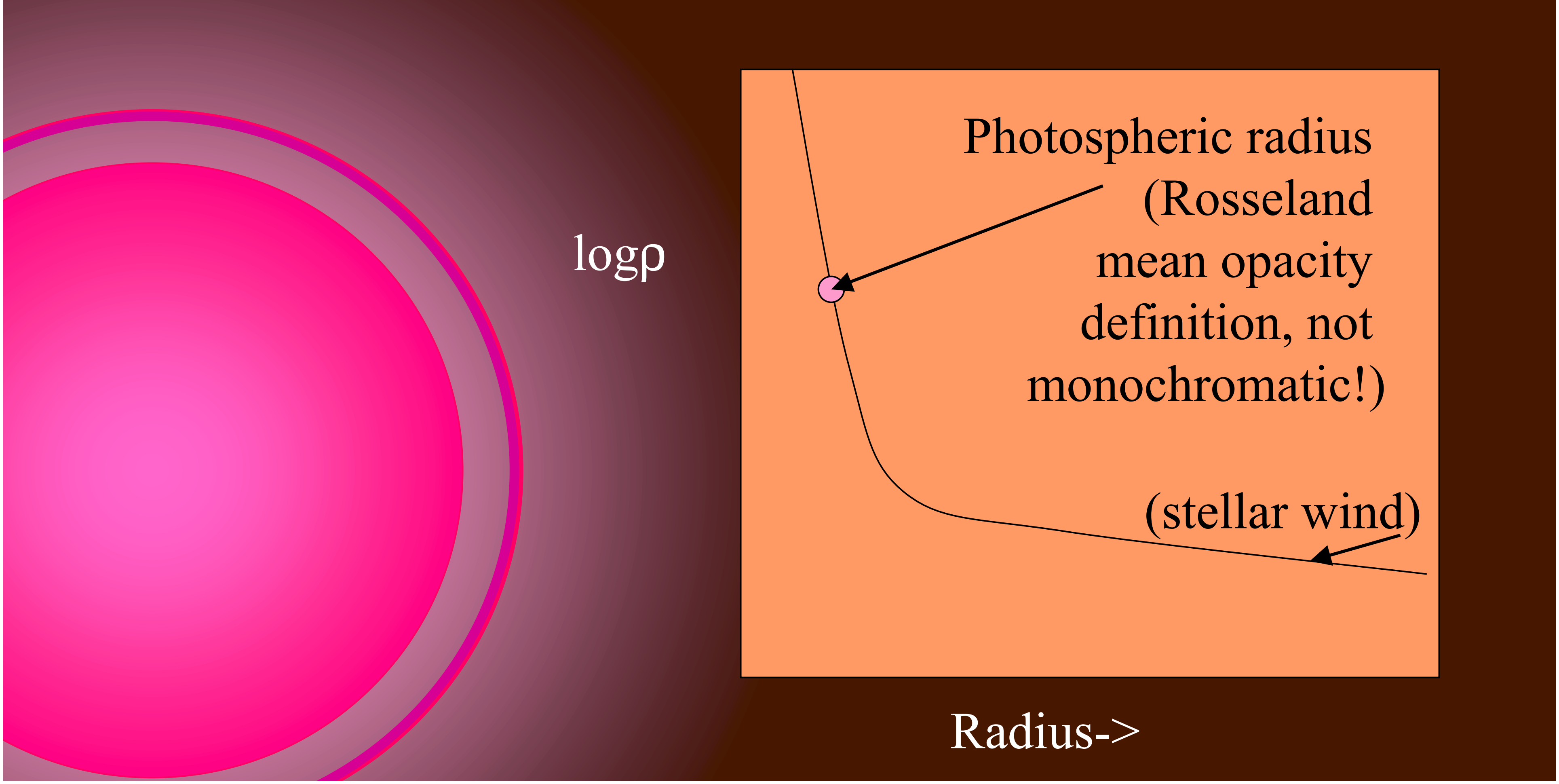


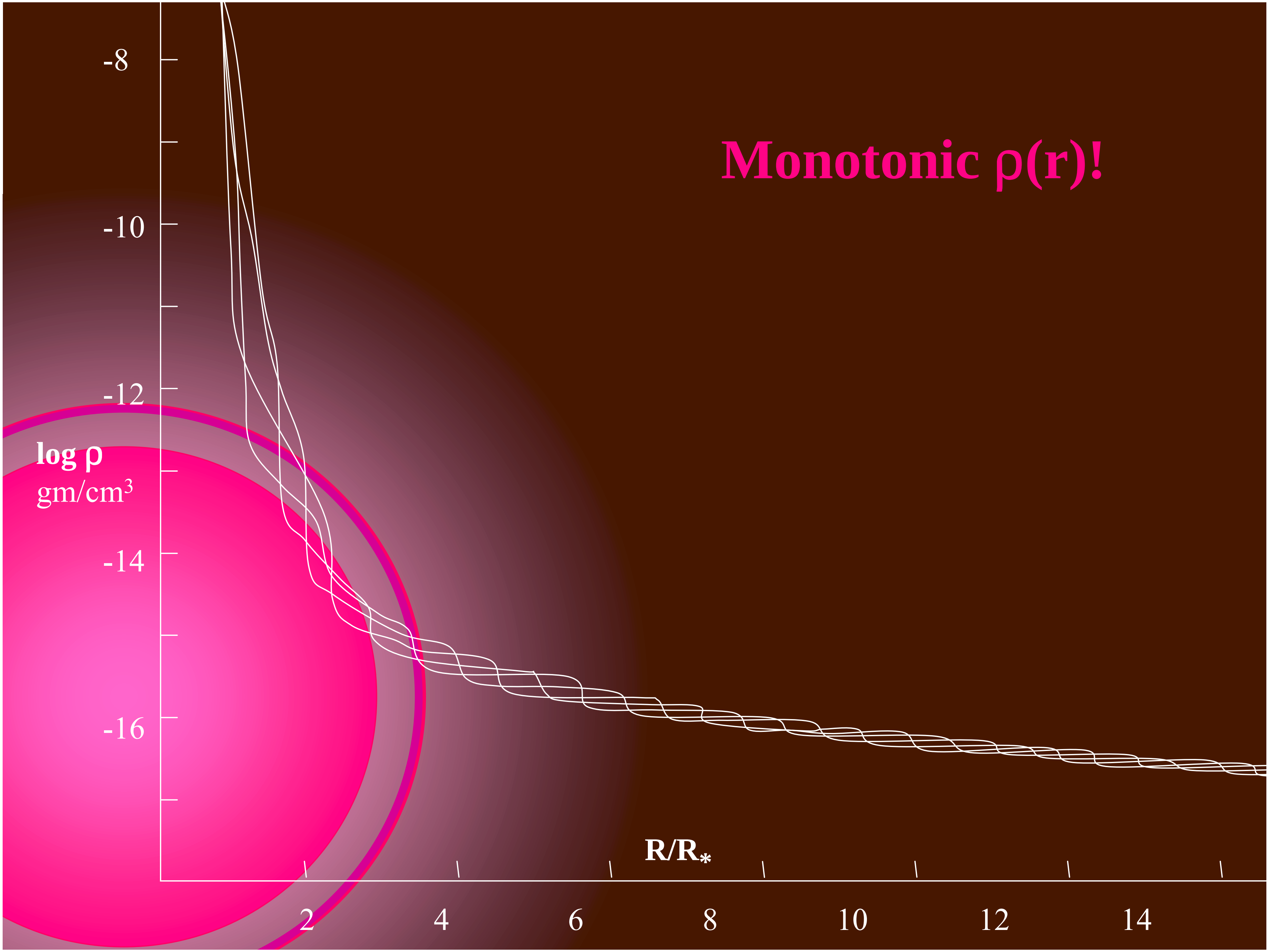
Evolutionary importance:

Miras signal the onset of the "superwind" that ends AGB evolution

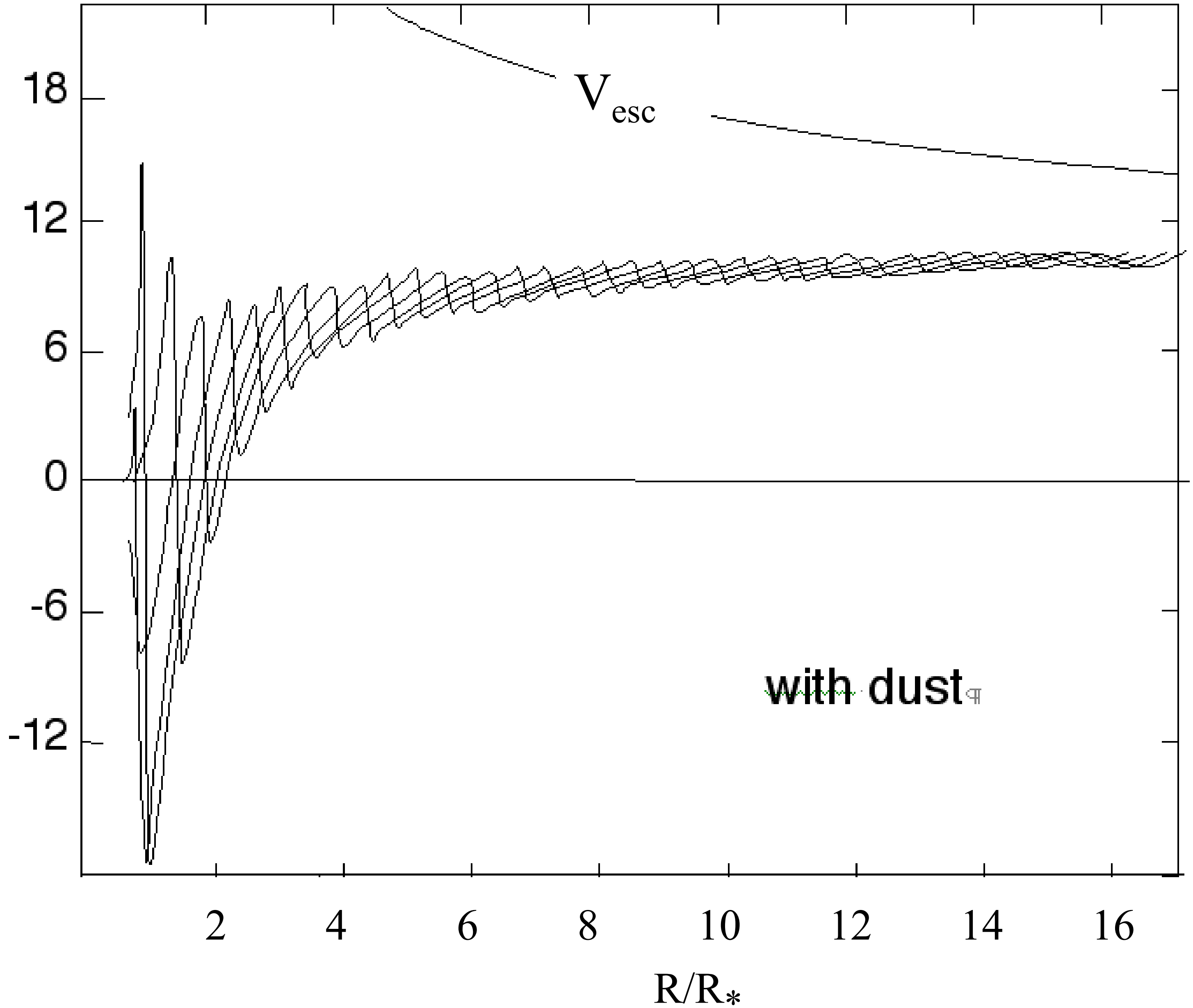
What would a Mira look like “up close”?

To first order, we should see an exponential decline in density merging into an inverse-square law decline

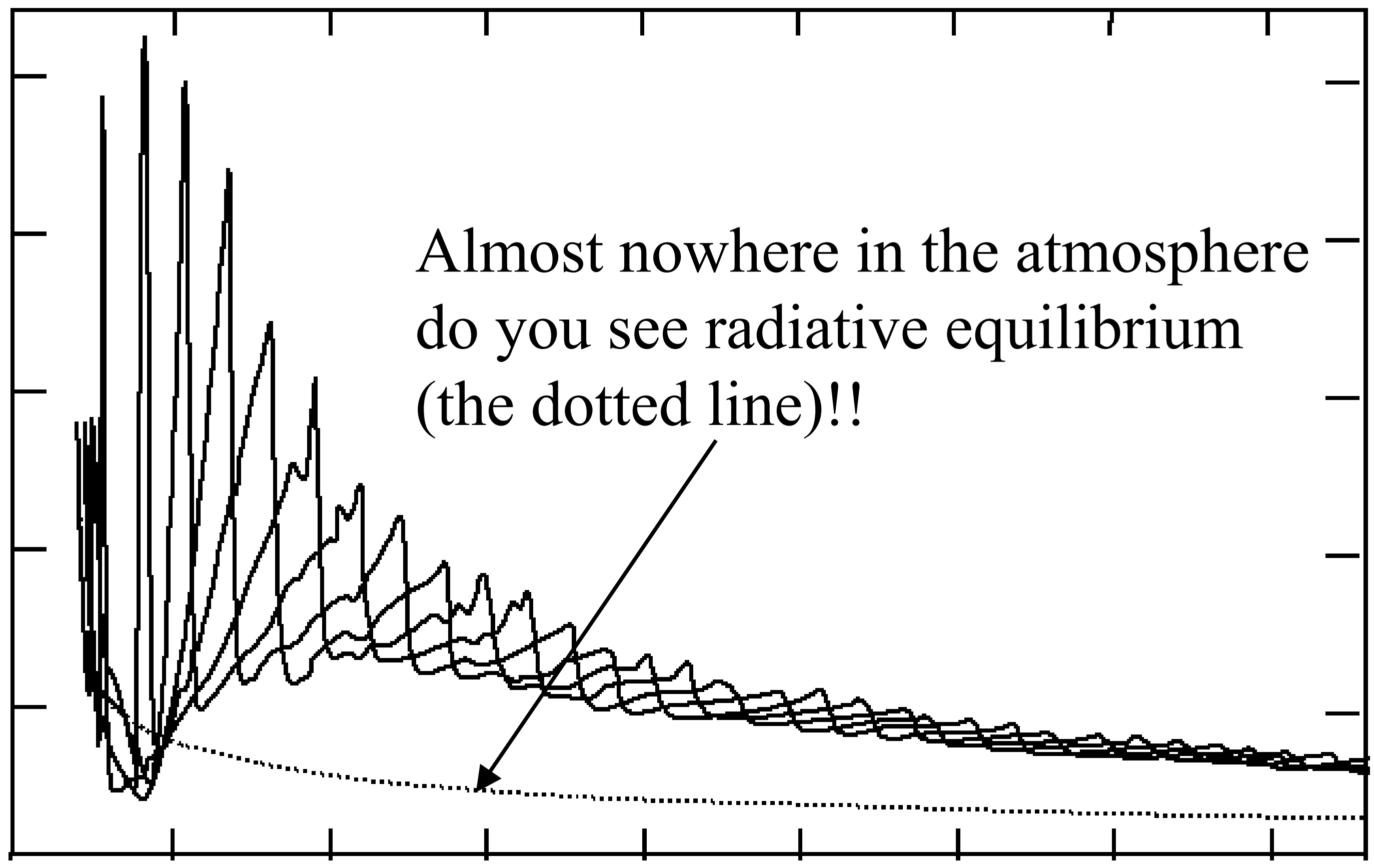


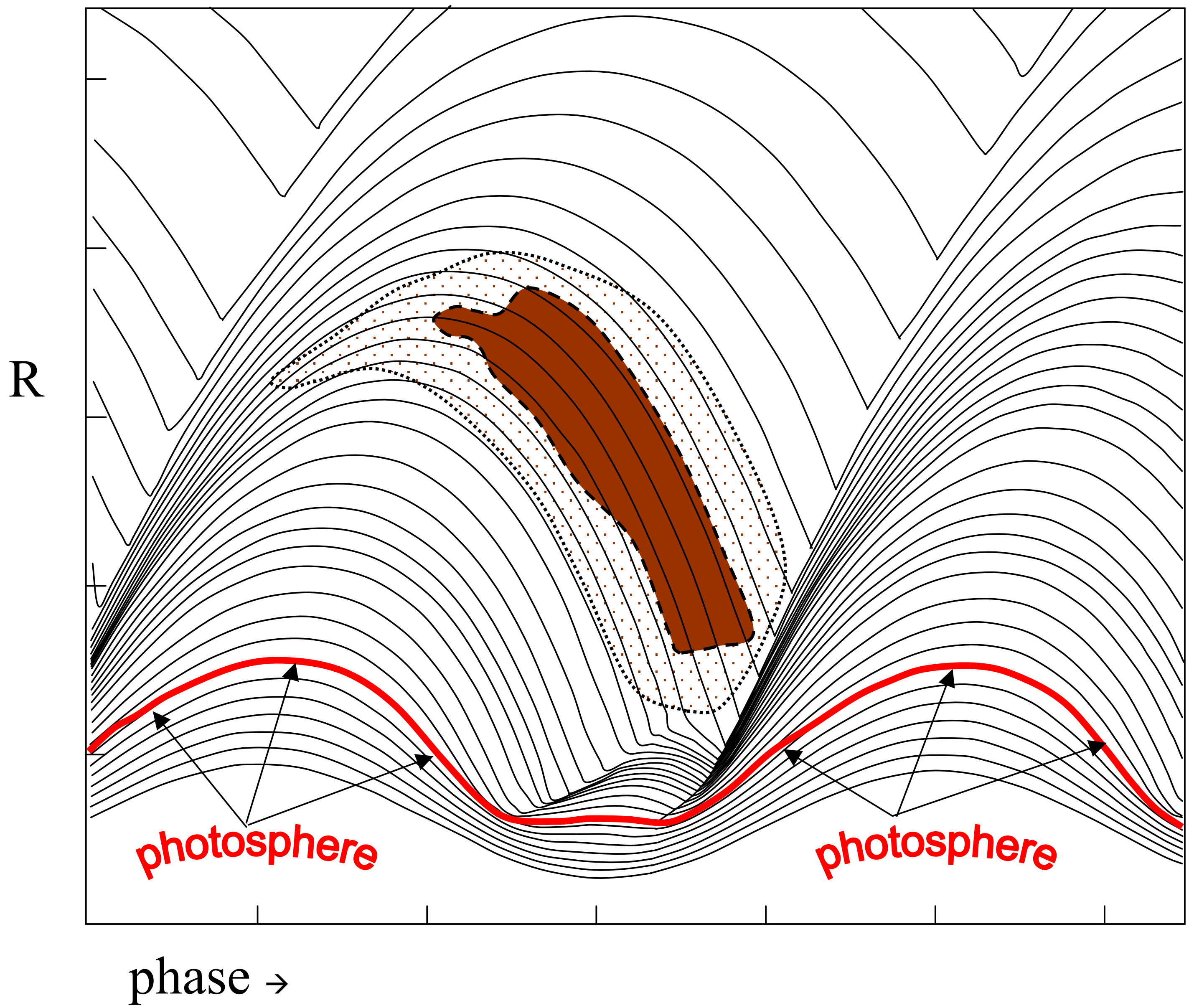

Monotonic ρ(r)!
log ρ
gm/cm3
-8
-10
-12
-14
-16
R/R*
2
4
6
8
10
12
14

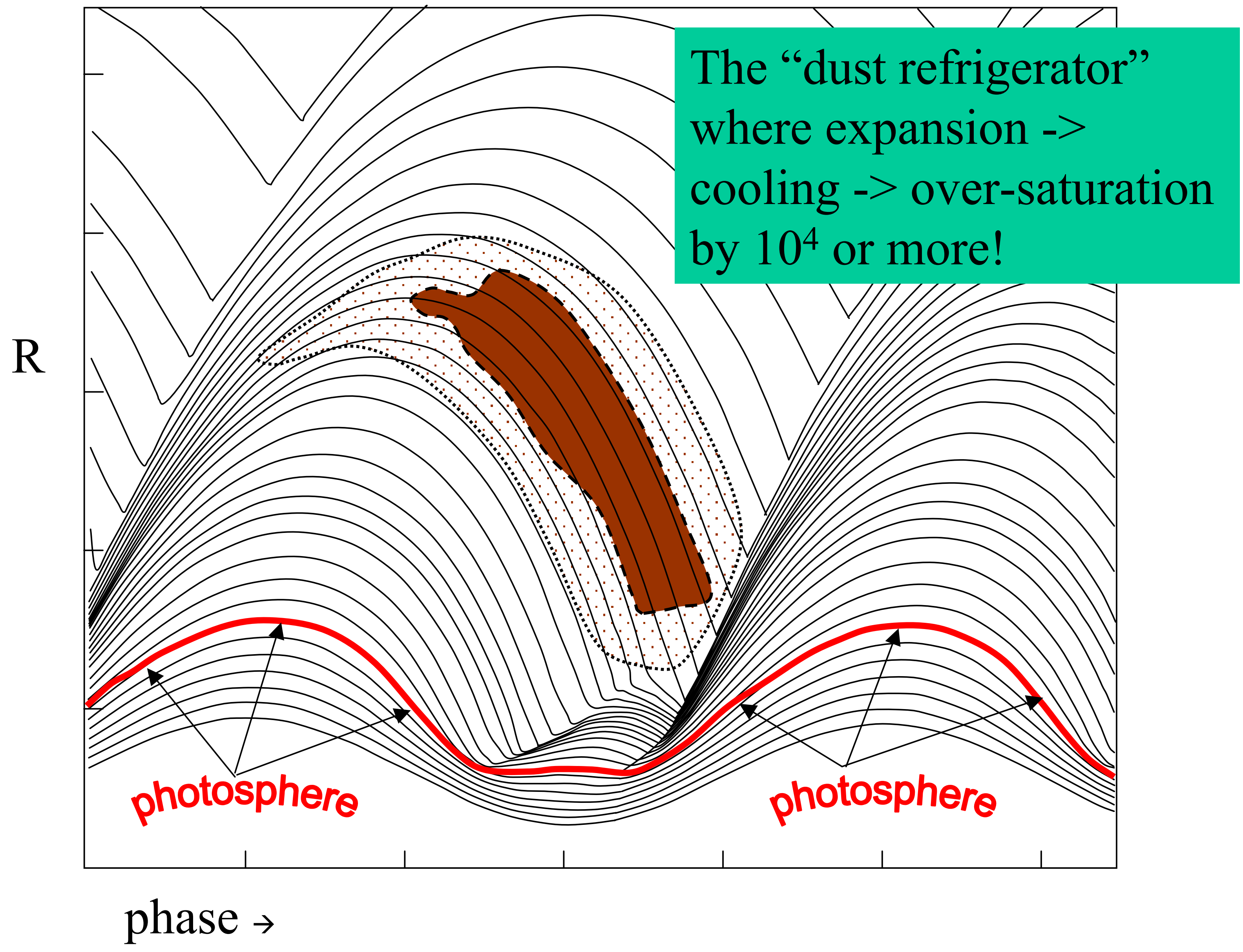
Shocks form and propagate outward



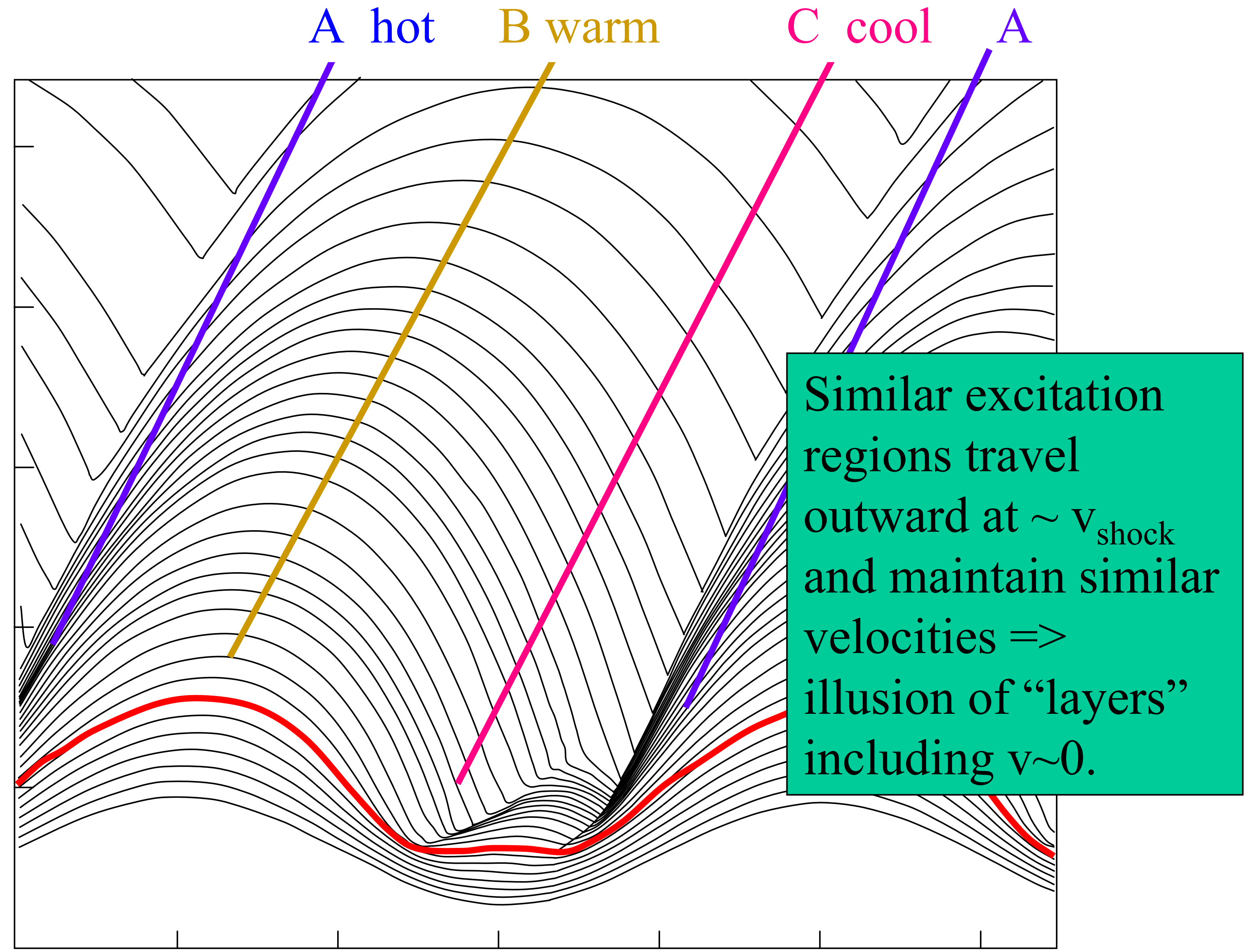
Shock compression -> heating -> radiative losses;
expansion between shocks -> cooling and slower radiative gains.




R
phase →
photosphere
photosphere

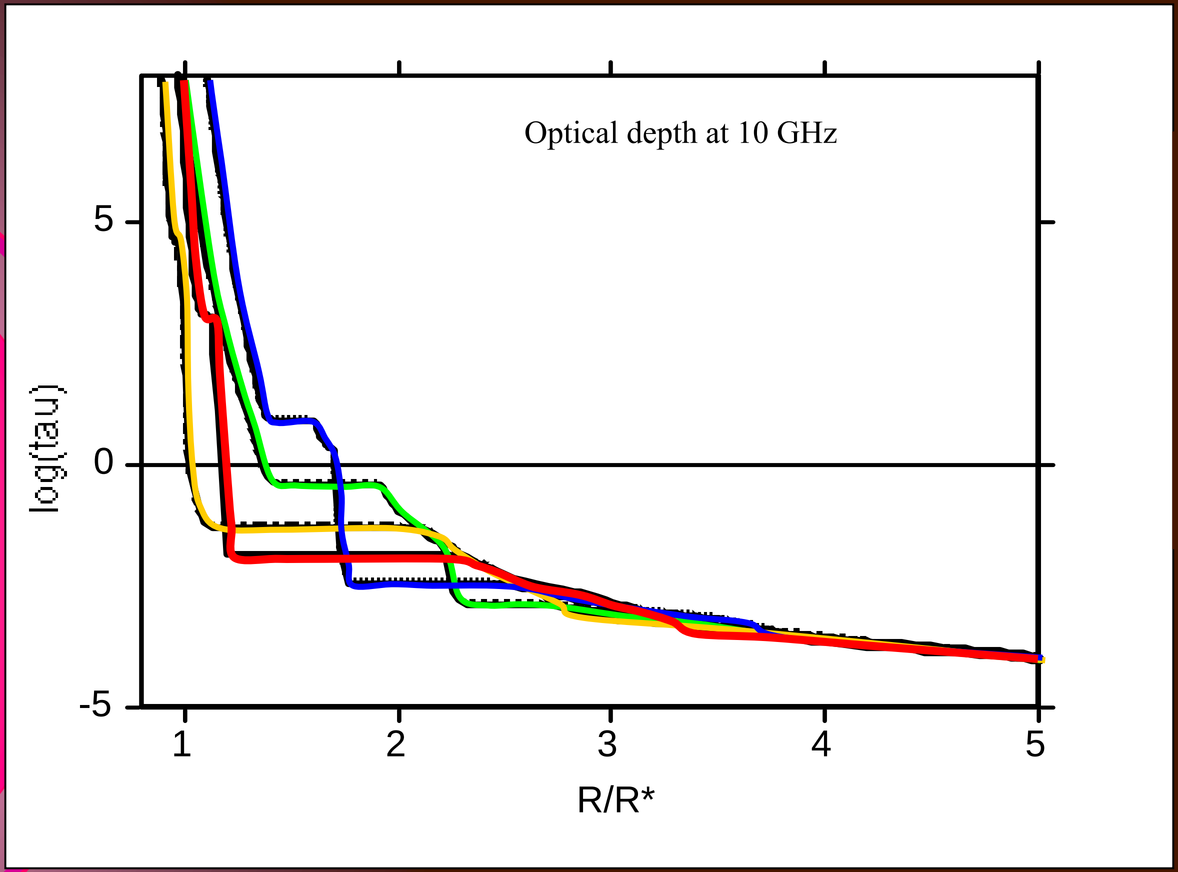


The "dust refrigerator"
where expansion ->
cooling -> over-saturation
by 10^4 or more!
R
phase →
photosphere
photosphere

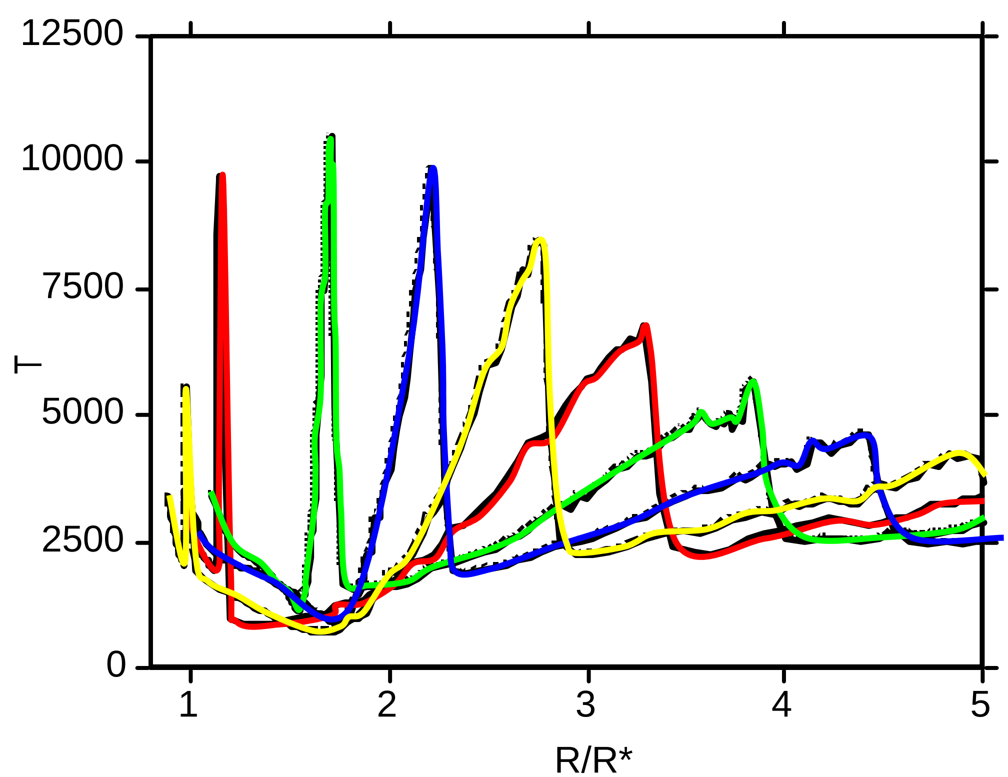


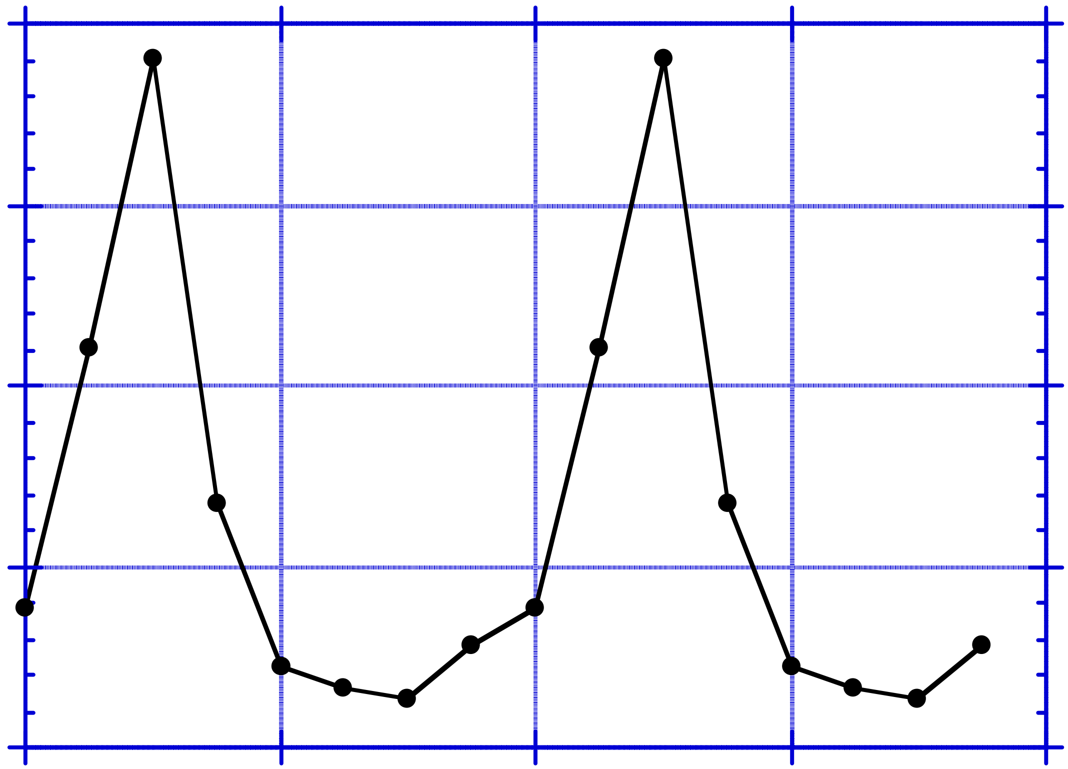
A hot
B warm
C cool
A
Similar excitation regions travel outward at ~ v_{shock} and maintain similar velocities => illusion of “layers” including v~0.

In some parts of the spectrum, what you should see is an expanding shock front that becomes transparent at some phase, revealing the next rising shock front:



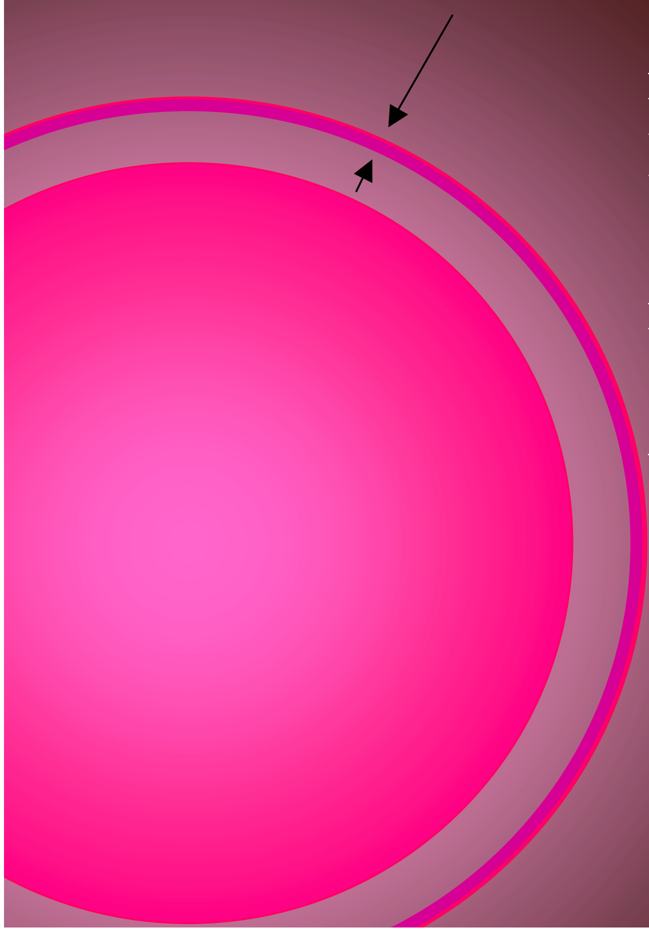
In these shocks, TR^2 is nearly constant over most of the cycle





Summary: The structure of the atmosphere

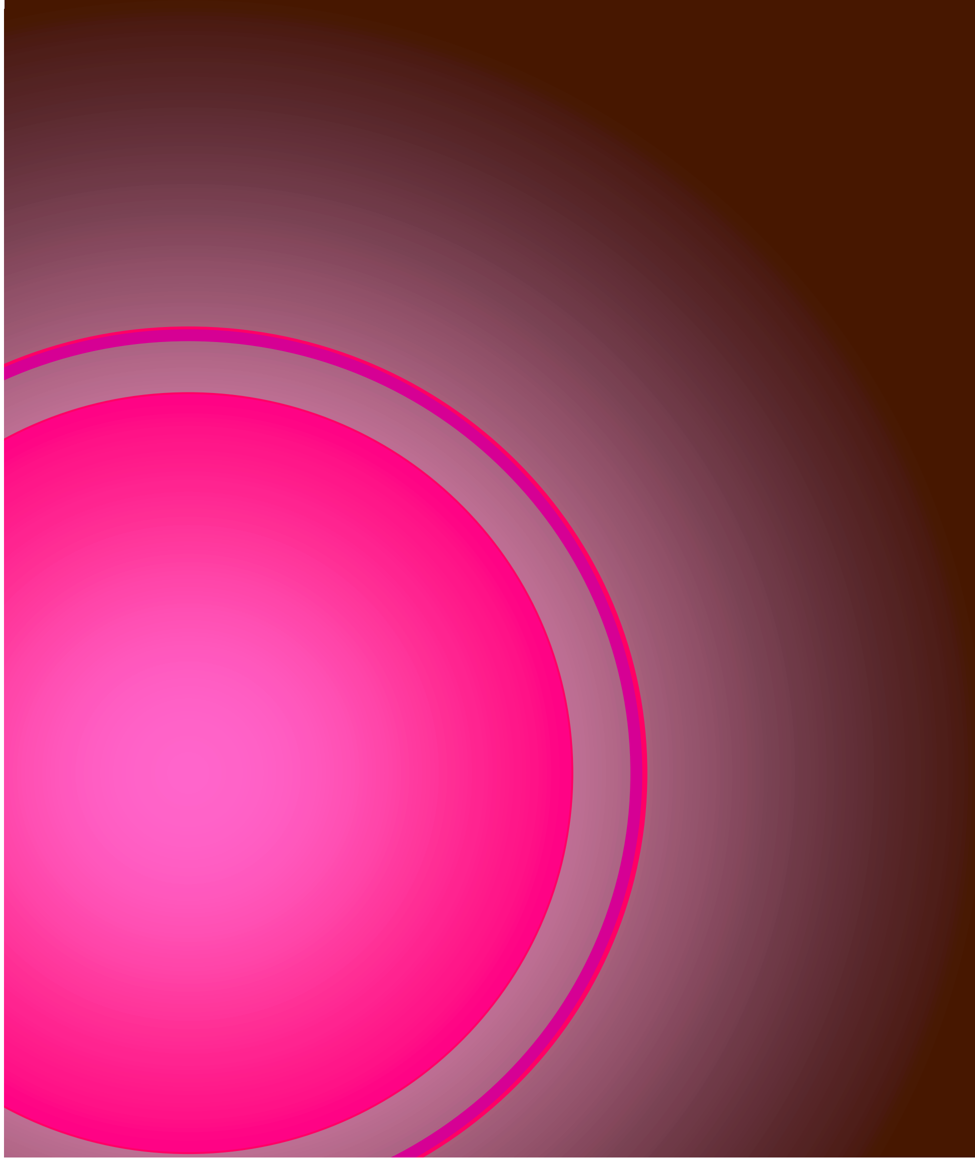
The density declines first steeply, then more slowly, monotonically, but with steps at the shocks.



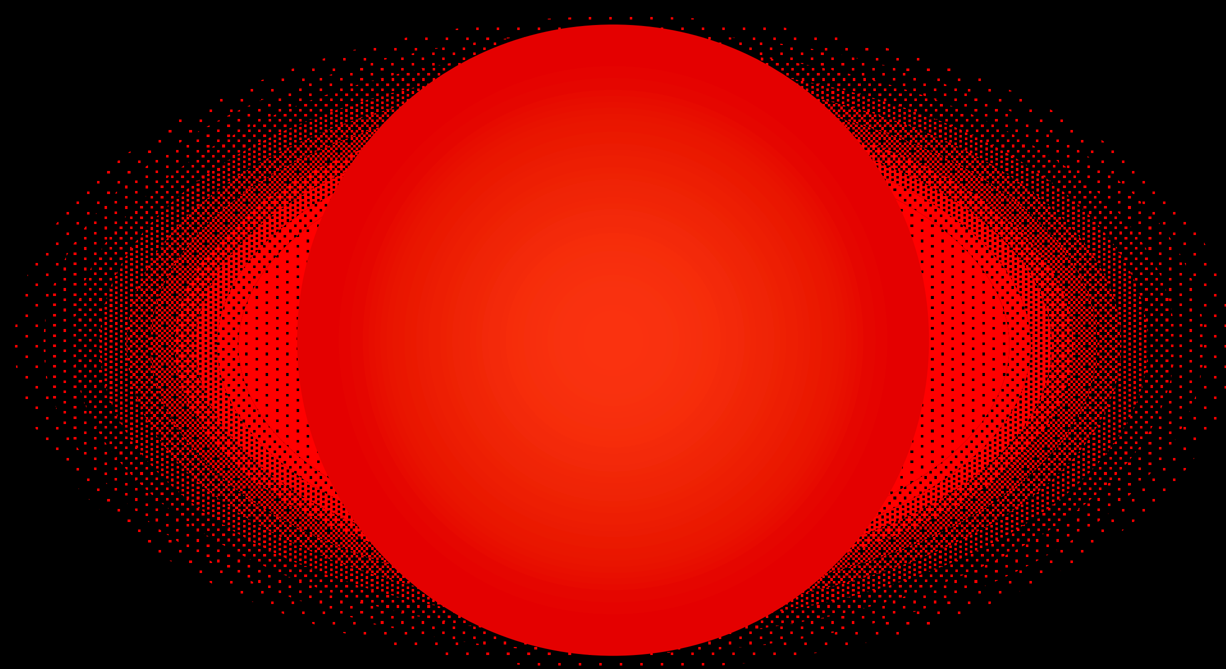
The temperature rarely matches the radiative equilibrium temperature.
Behind shocks, T rises to several thousand K; after expanding, T may be less than the radiative equilibrium temperature.
This effect creates the “dust refrigerator” where super-saturation exceeds x10^4

Large portions of the atmosphere are “falling in” at any given time.

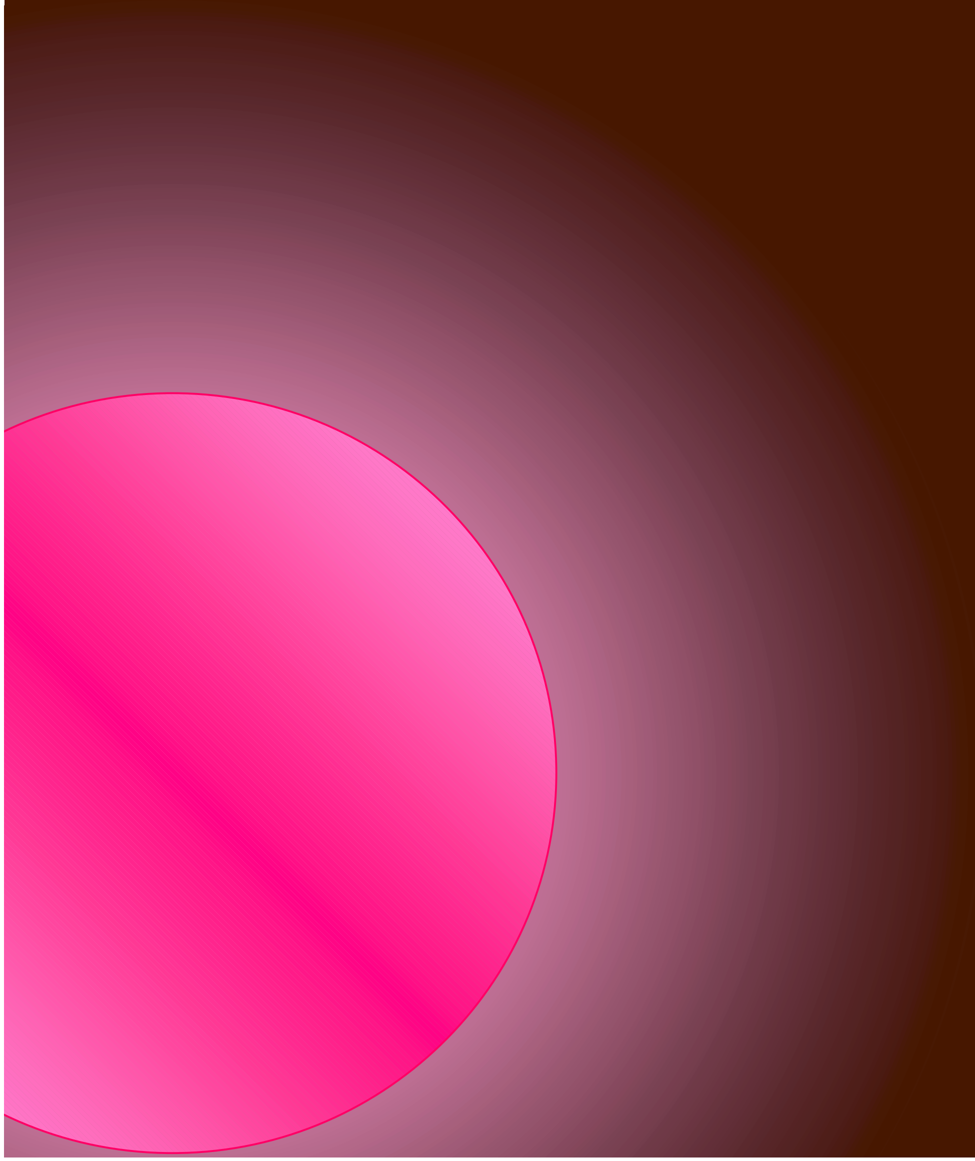
What might cause departures from spherical symmetry?



Scattering in a circumstellar envelope leads to shape distortions when observed in polarized light



Atmospheric deviations from spherical symmetry may result from:



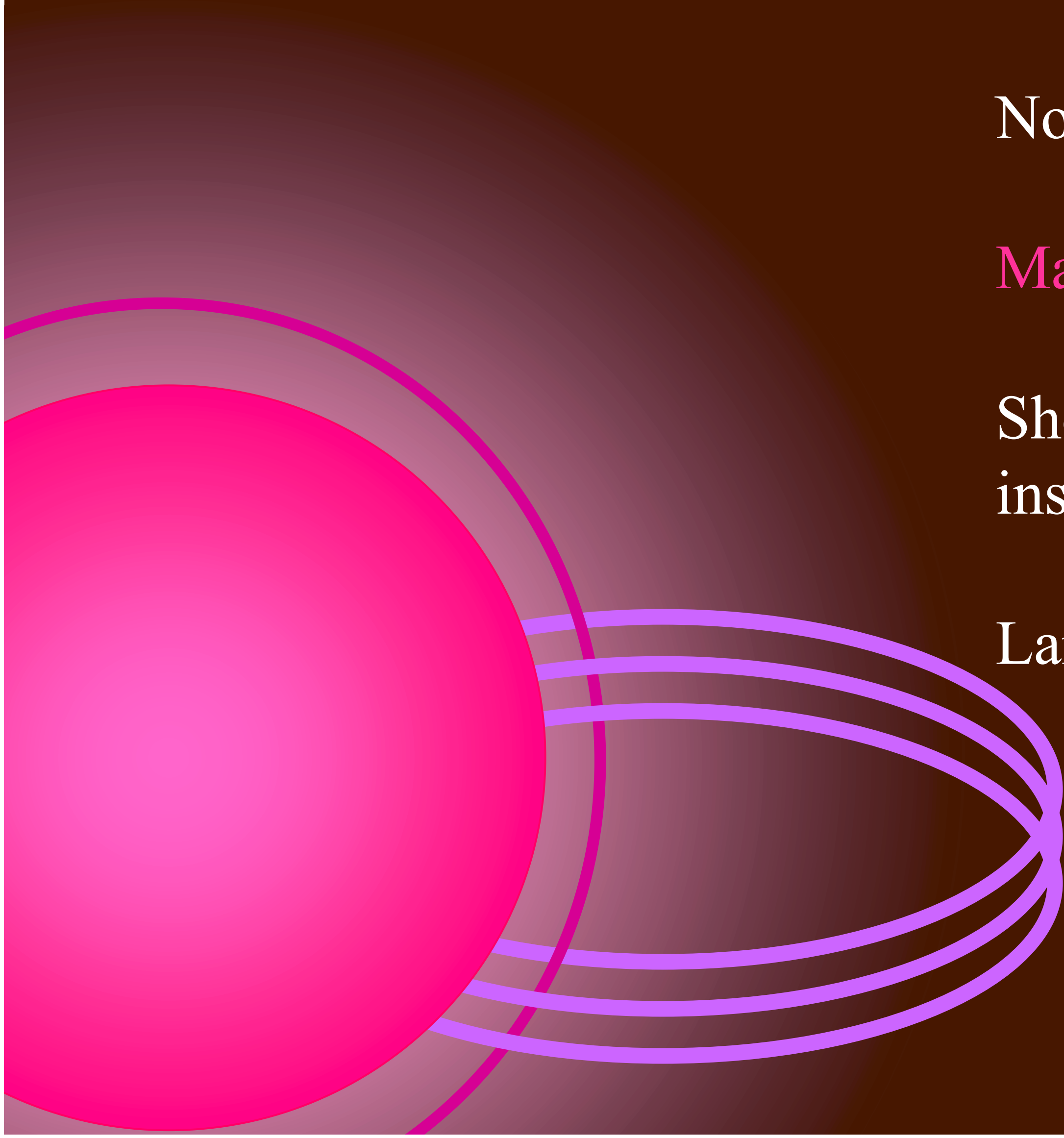
Non-radial pulsation

Magnetic field structures

Shock propagation instabilities

Large convective cells

Atmospheric deviations from spherical symmetry may result from:



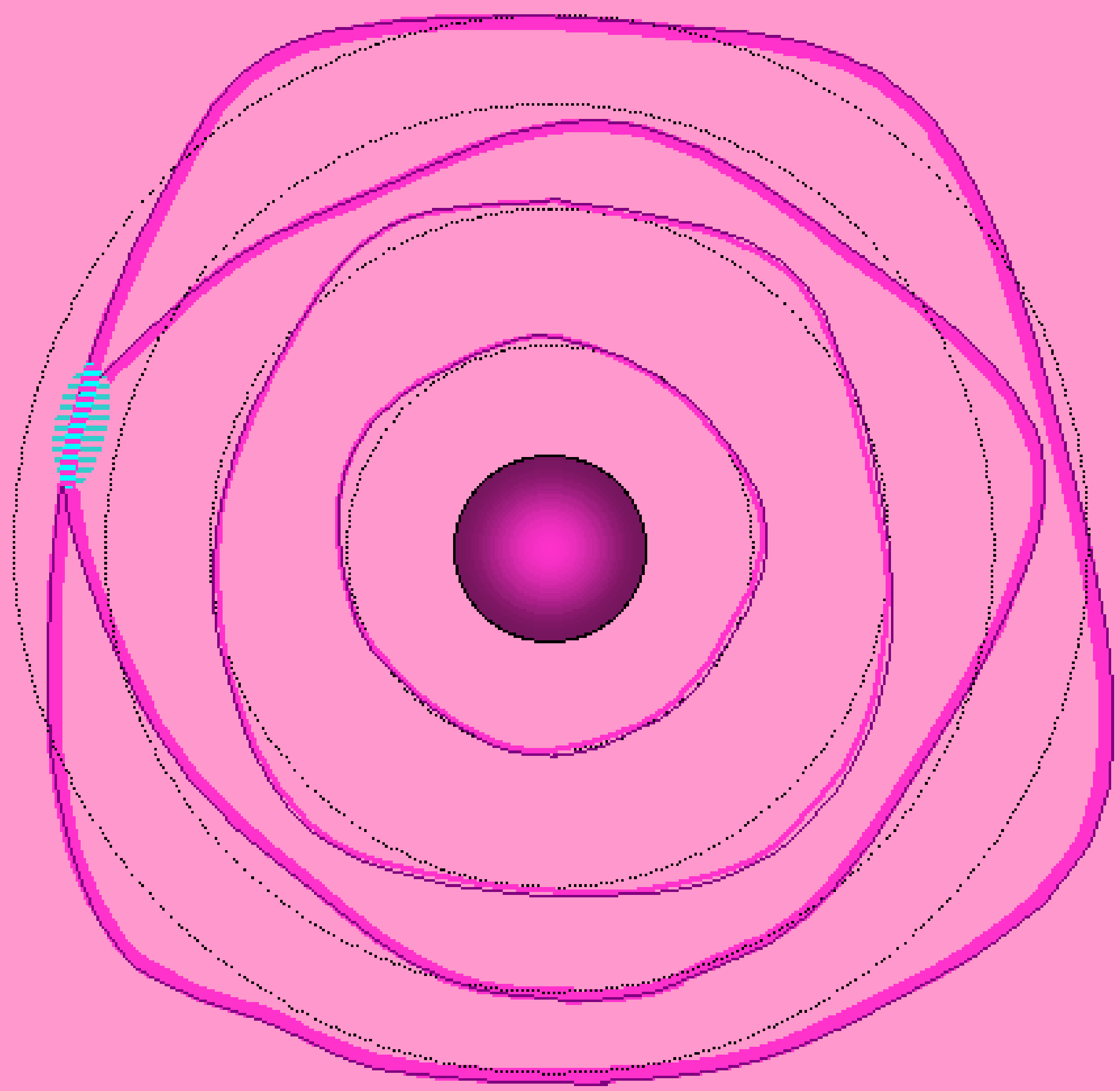
Non-radial pulsation

Magnetic field structures

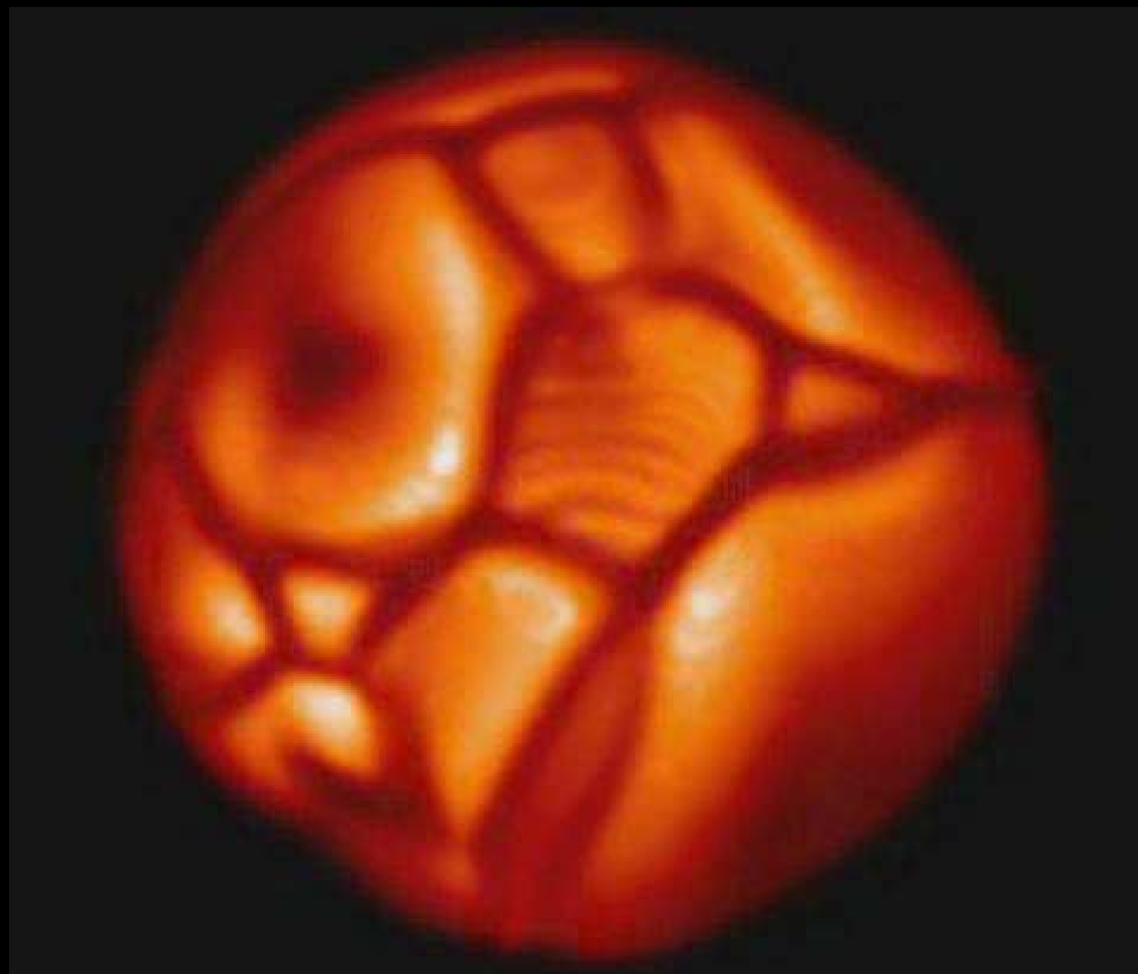
Shock propagation instabilities

Large convective cells

Aperiodic shock propagation can lead to shocks "bunching up" and coalescing. Coalesced shocks will appear as bright spots.

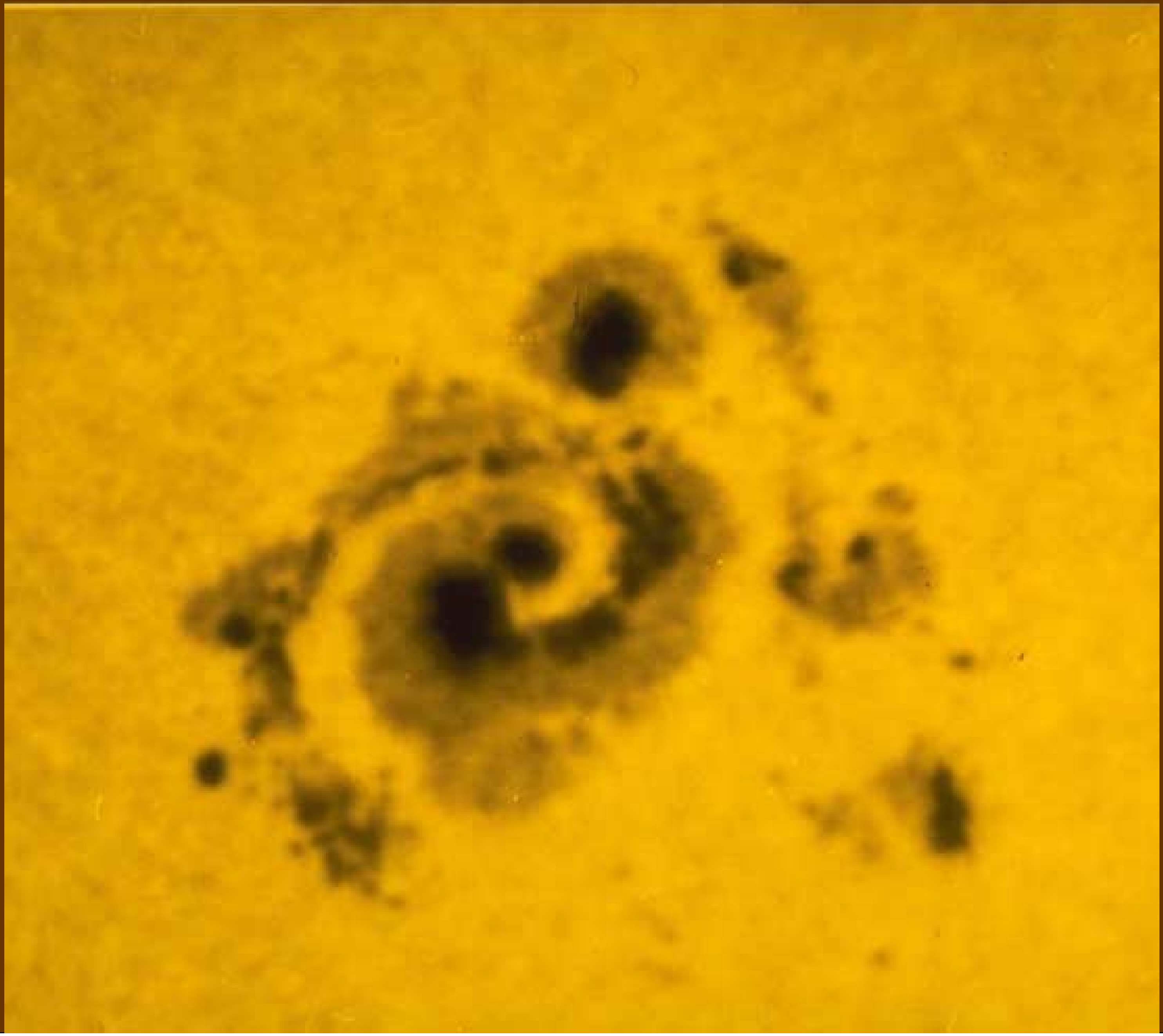


Simulations of convection in giant stars suggest that these could produce large, even bipolar, structures:

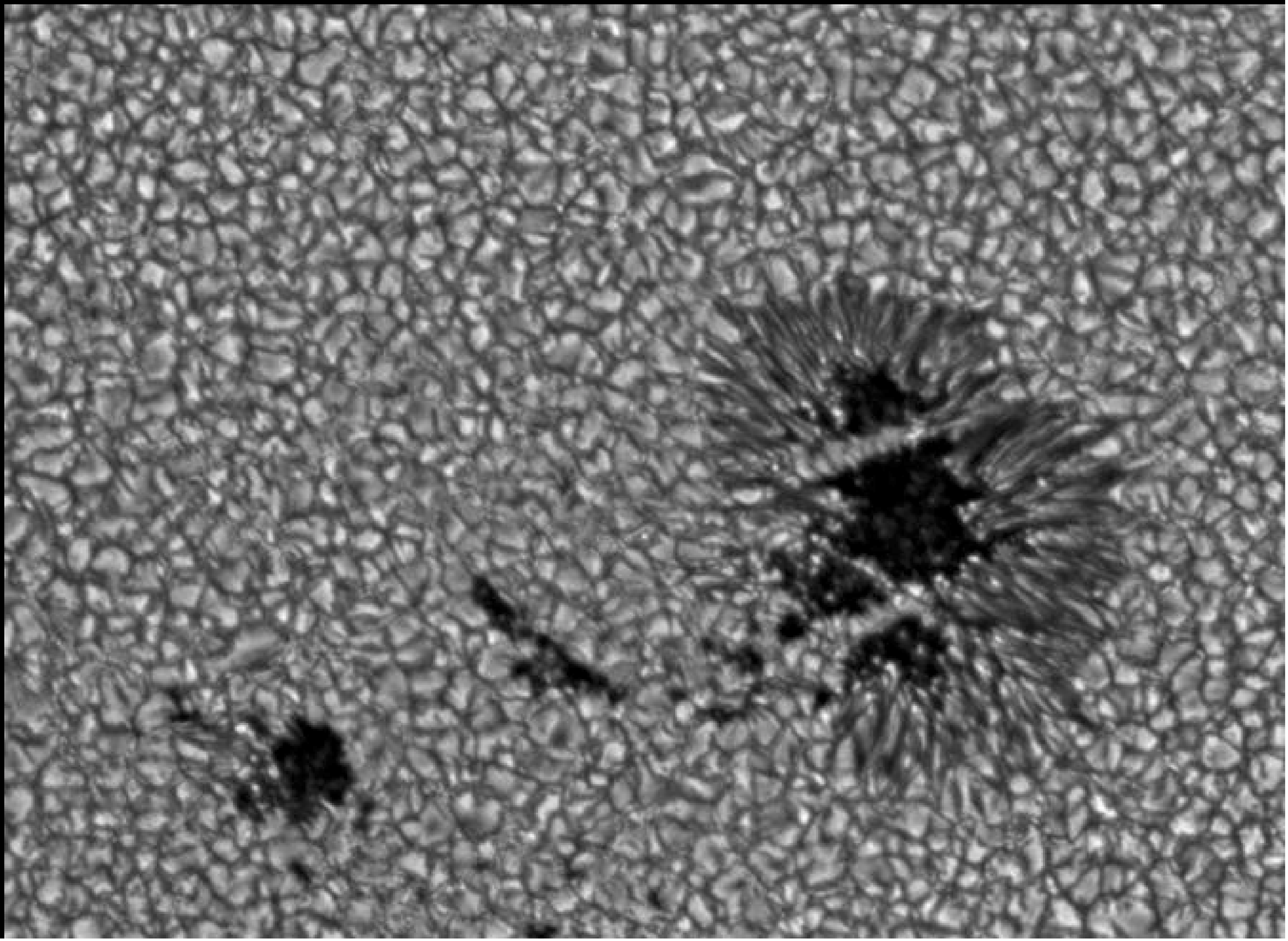


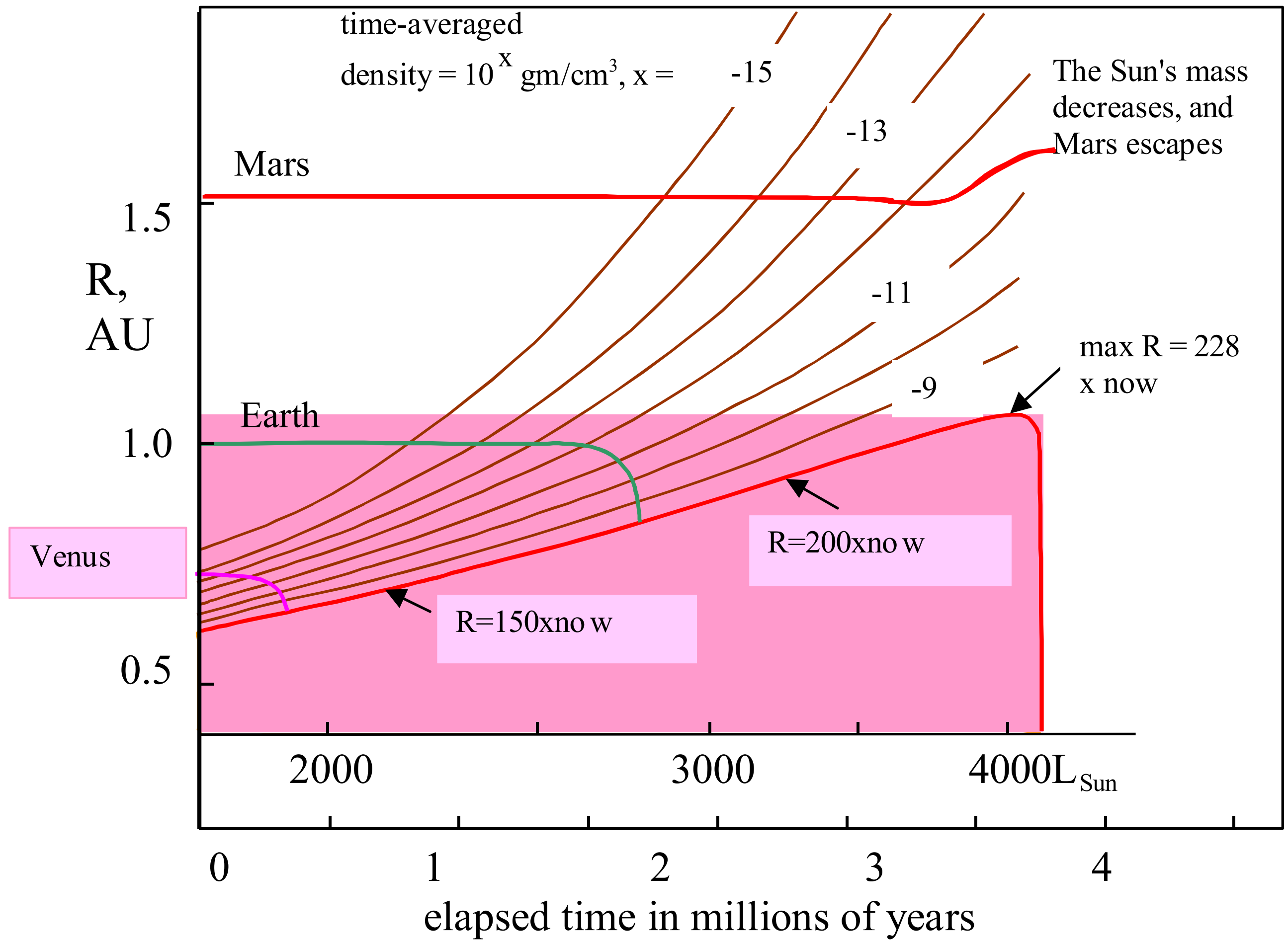
Freytag, 2000 - see http://www.astro.uu.se/~bf/movie/movie.html

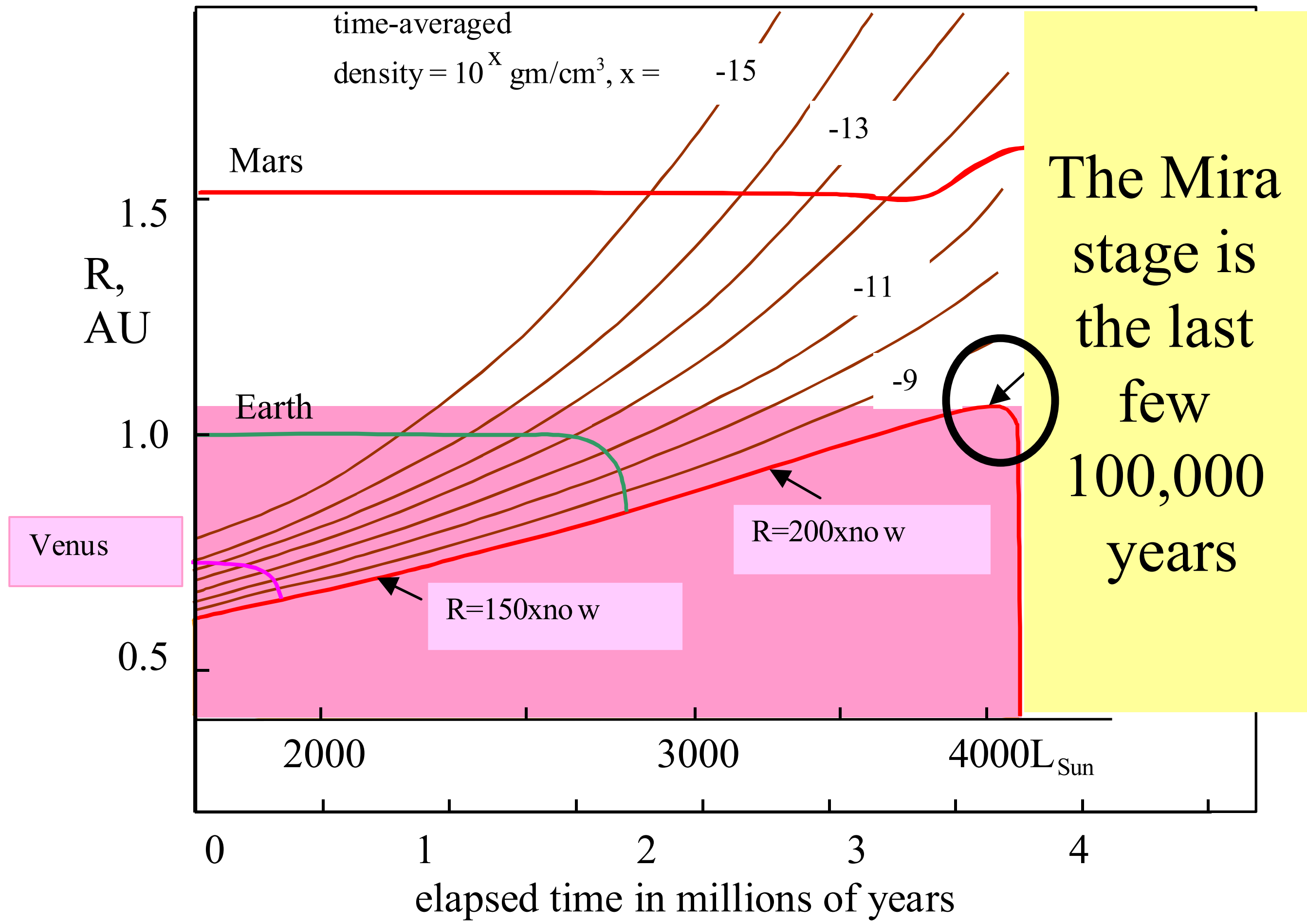
Of course, starspots belong on the list:



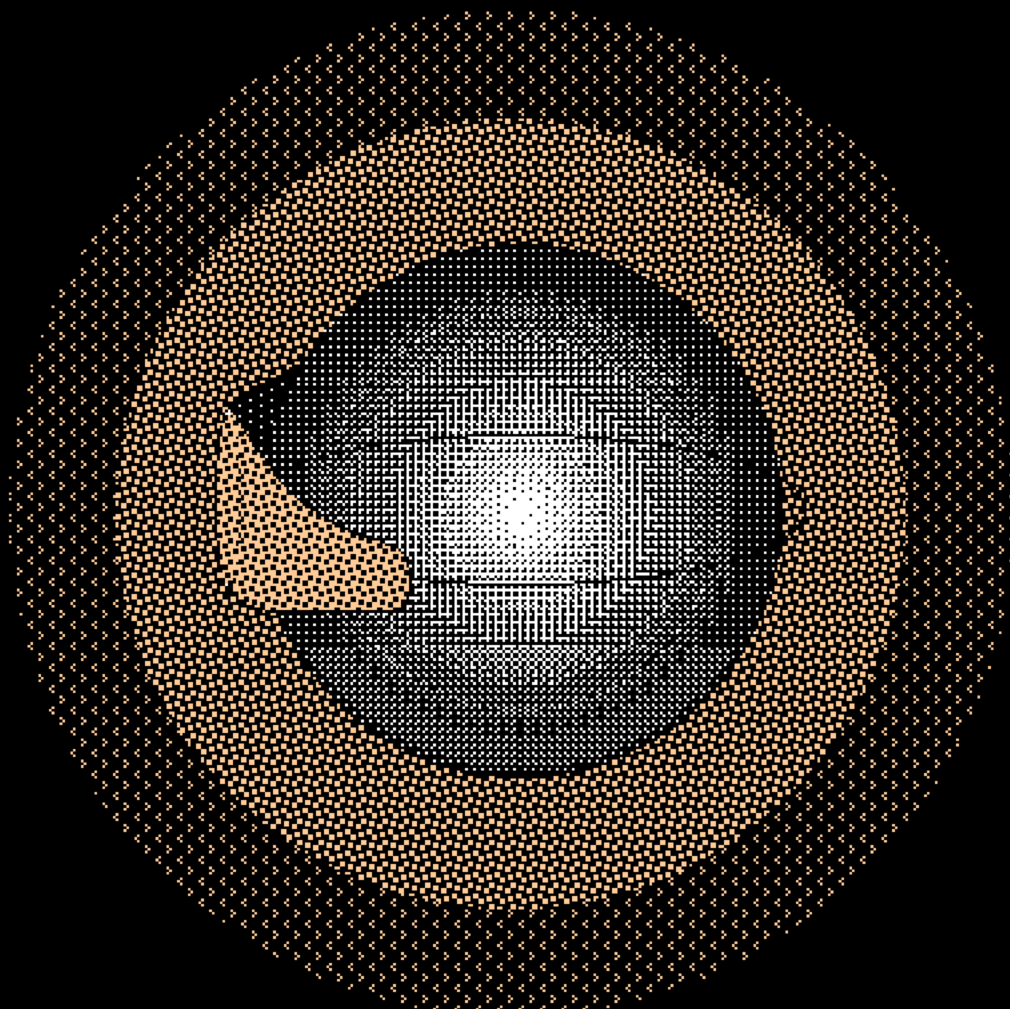
Or perhaps spots with granulation:

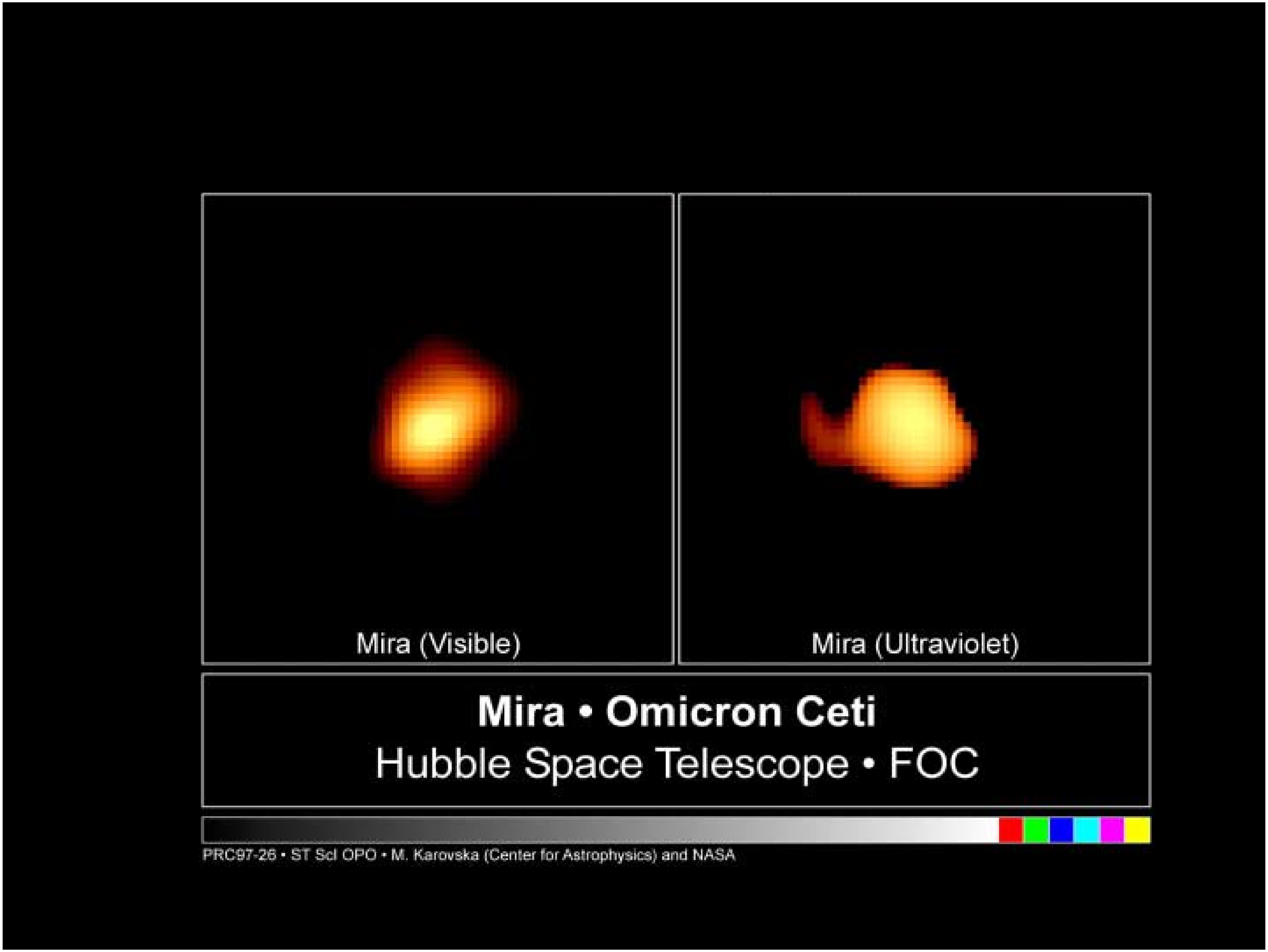



time-averaged
density = 10^x gm/cm^3, x =
-15
-13
-11
-9
The Sun's mass decreases, and Mars escapes
Mars
1.5
R, AU
1.0
0.5
Earth
Venus
max R = 228 x now
R=200xno w
R=150xno w
2000
3000
4000L Sun
0
1
2
3
4
elapsed time in millions of years


time-averaged
density = 10^x gm/cm³, x =
-15
-13
-11
-9
Mars
Earth
Venus
1.5
R,
AU
1.0
0.5
R=200xnow
R=150xnow
2000
3000
4000L Sun
0
1
2
3
4
elapsed time in millions of years
The Mira stage is the last few 100,000 years

Planets orbiting in Mira winds will produce wakes and shocks; these could give the impression of a non-symmetric or a spotted star.




Mira (Visible)
Mira (Ultraviolet)
Mira • Omicron Ceti
Hubble Space Telescope • FOC
PRC97-26 • ST ScI OPO • M. Karovska (Center for Astrophysics) and NASA

Summary: Departures from spherical symmetry

Nonradial pulsation,
convection,
shock instabilities,
magnetic fields,
spots,
companions,
or the interaction
of a planet with the
Mira wind.

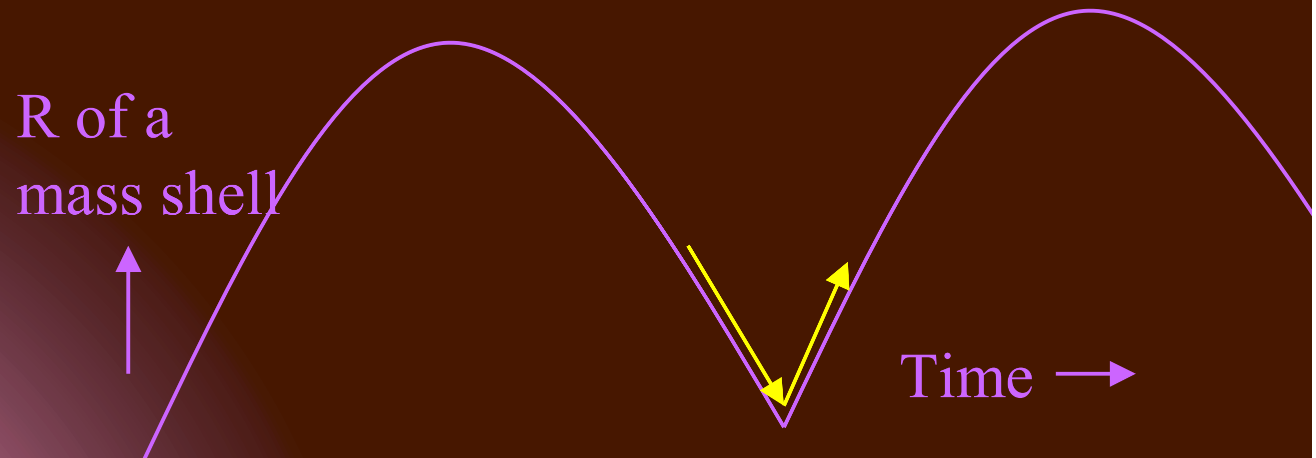
How big are these stars, anyway?

Pulsation models (e.g. Ostlie & Cox):
F mode => radii in AU
approximately equal to pulsation period in days,
while overtone pulsation would give radii
about 1.5 to 2 times larger.

Size <--> Mode identification

Dynamical atmosphere models
=> quite strongly that Miras are
fundamental mode pulsators,
R ~ 1 to 2 AU in most cases.

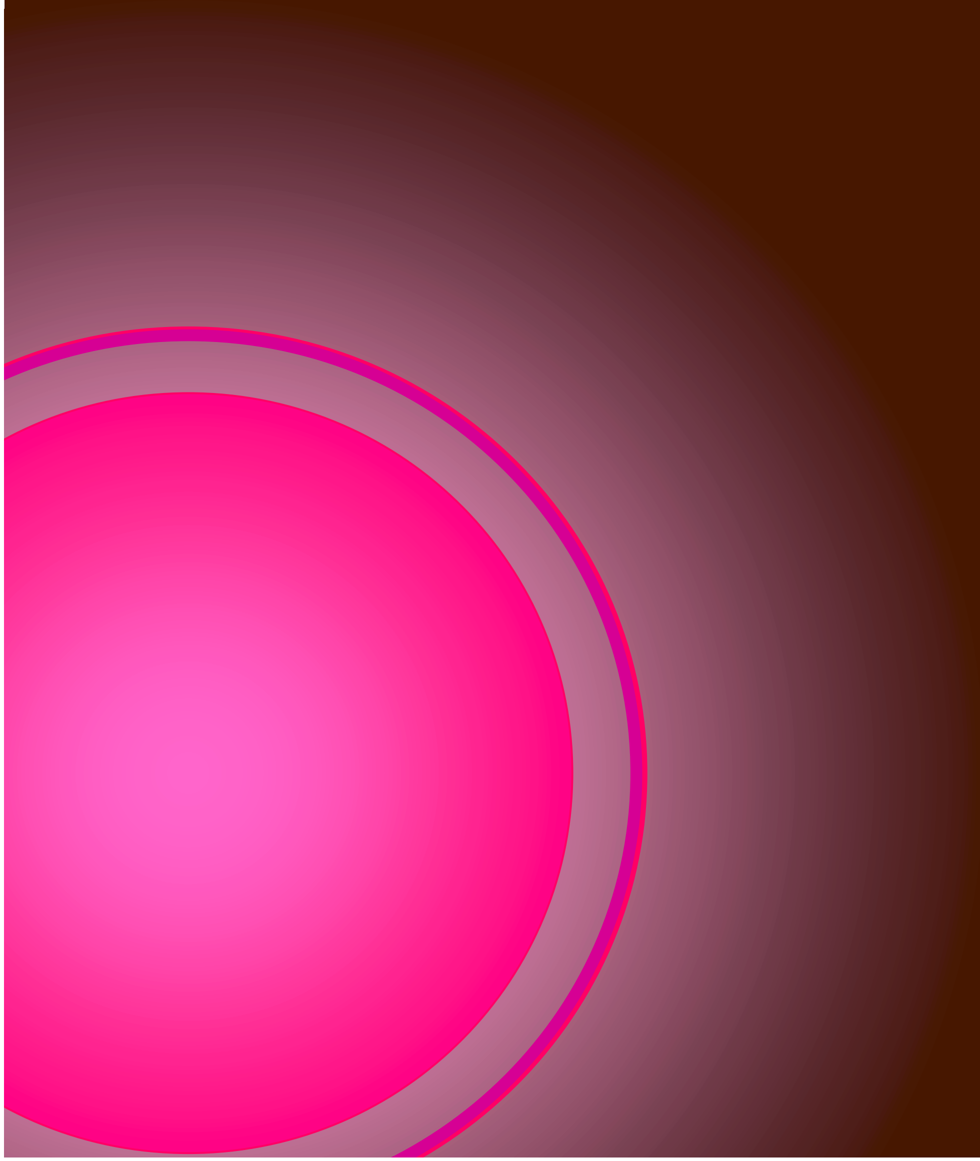
Argument 1: Observed shock amplitudes require higher g or v-escape than any overtone pulsators can have.



Plane-parallel: $\Delta v = gP$
However usually $\Delta R/R$ is large enough to require a slightly messier formula.
(Hill & Willson 1979; see Willson 2000 ARAA.)

Argument 2: Wave propagation theory:

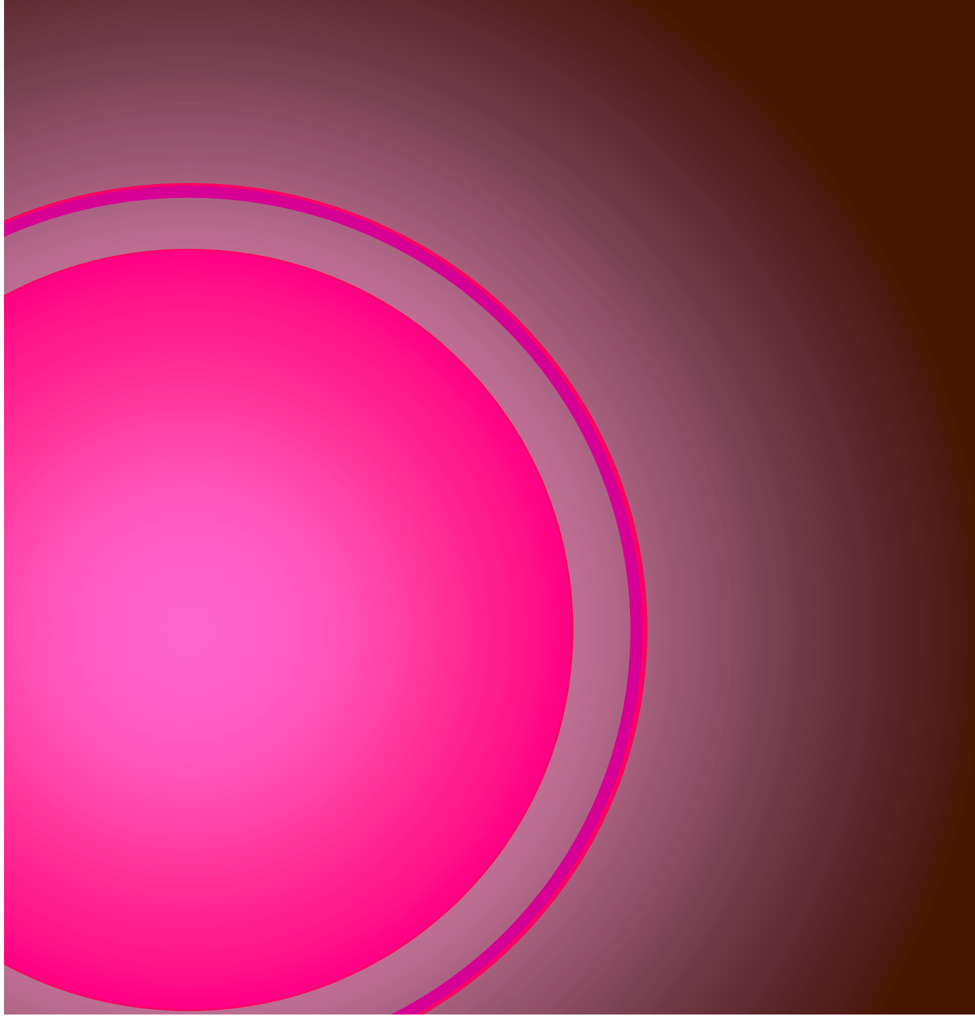
If $P < P_{acoustic}$, waves propagate with little damping.



Wave propagation theory:

If $P < P_{acoustic}$, waves do not reflect near the photosphere.

Reflection is necessary to get buildup of large amplitudes.



Wave propagation theory:

If $P < P_{acoustic}$, waves do not reflect near the photosphere.

Reflection is necessary to get buildup of large amplitudes.

Therefore, large amplitude pulsation generally occurs only for $P >$ or $\gg P_{acoustic}$.

Wave propagation theory:

If $P < P_{acoustic}$, waves do not reflect near the photosphere.

Reflection is necessary to get buildup of large amplitudes.

Therefore, large amplitude pulsation generally occurs only for $P >$ or $\gg P_{acoustic}$.

$$P_{acoustic} \sim 2\pi H / c_{sound}$$

For AGB stars, typically

$$P_{fundamental} > P_{acoustic} > P_{overtone}$$

Wave propagation theory:

If $P < P_{acoustic}$, waves do not reflect near the photosphere.

Reflection is necessary to get buildup of large amplitudes.

Therefore, large amplitude pulsation generally occurs only for $P >$ or $\gg P_{acoustic}$.

$$P_{acoustic} \sim 2\pi H / c_{sound}$$

For AGB stars, typically

$$P_{fundamental} > P_{acoustic} > P_{overtone}$$

Therefore, large amplitude overtone pulsation is NOT expected to occur.

Fix P (the observed quantity) and M (not free to vary by much and typically showing up in a square root).

Vary R and/or the driving amplitude to try to get a good model.

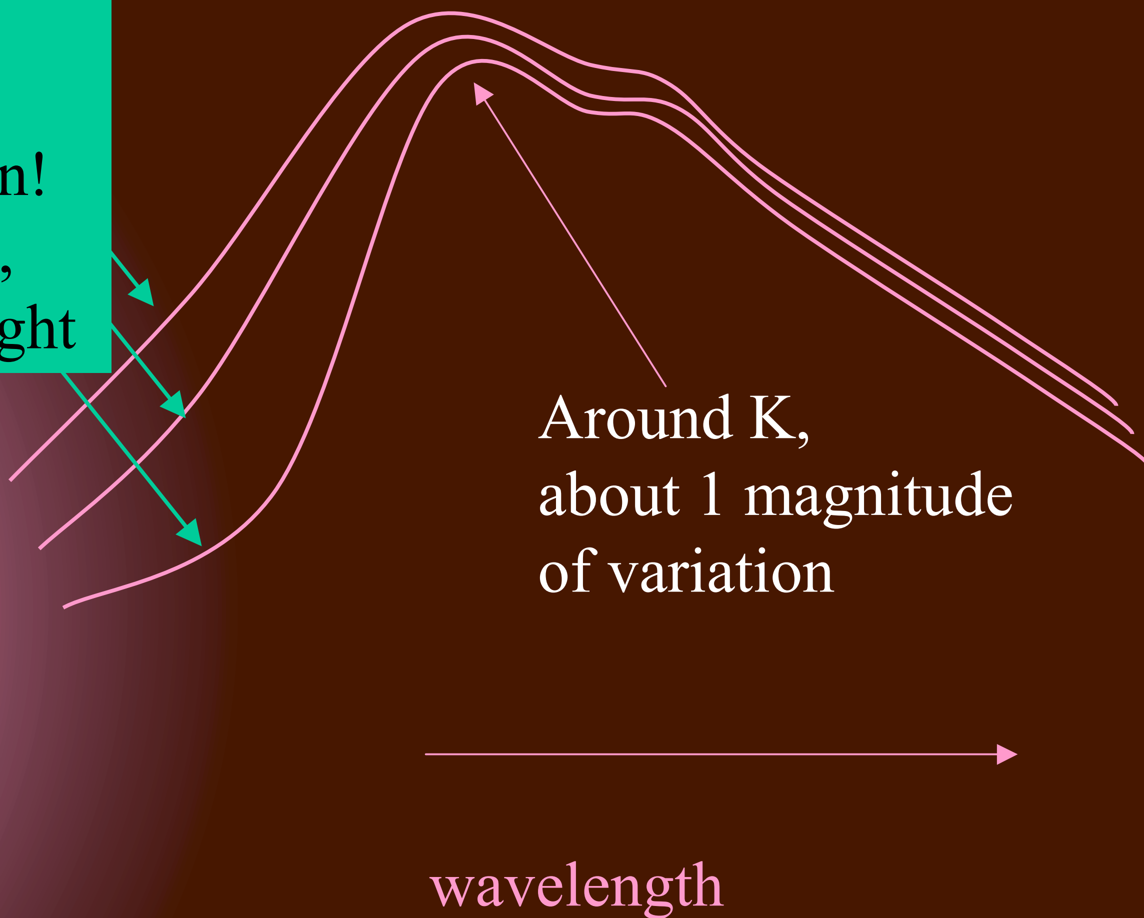
For F mode models: Easy!

For overtone models:
Doesn't work! Too much power needed -> larger amplitudes and even then the models are very irregular and ill-behaved.

(Bowen 1989 gives details)

Sketch of Mira SED

In the visible,
up to 6-7-8-9
magnitudes of variation!
There is no continuum,
even near maximum light



How big? How cool?

Highly probable:

M from 0.8 to 4-5 Ms_{un}

But most of them 1-2 Ms_{un}

For 1 Ms_{un},

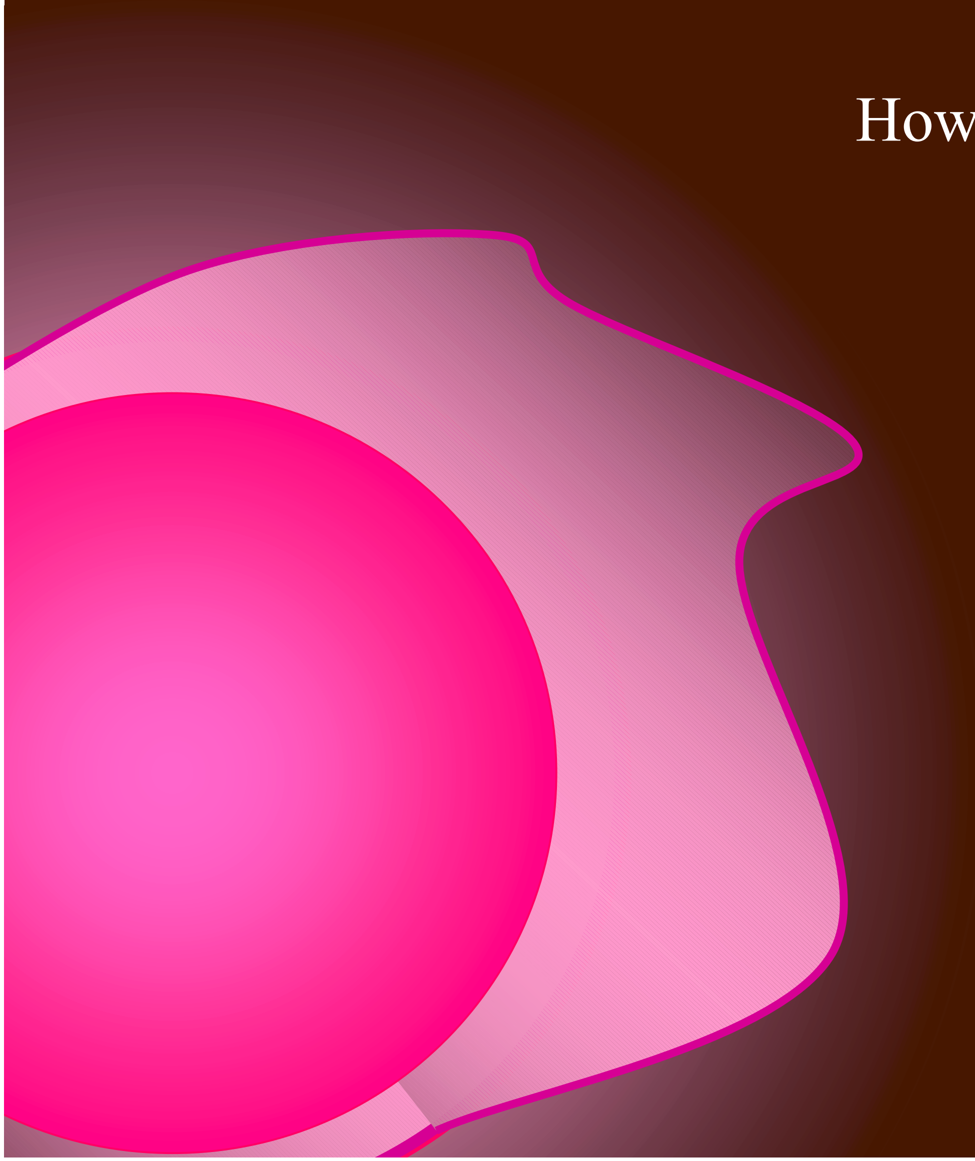
Mira L ~ 4000 L_{Sun}

Mira R ~ 200-250 Rs_{un}

Effective temperatures

nearly all ~3000-3500K

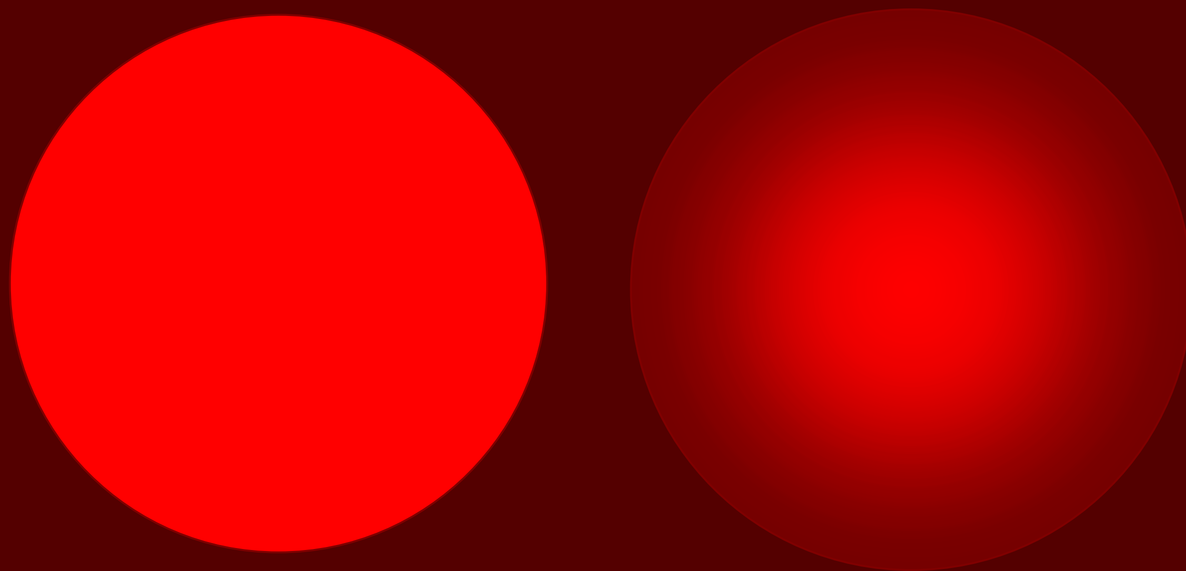
Conclusions: Interesting things to look for in interferometric observations of Miras:



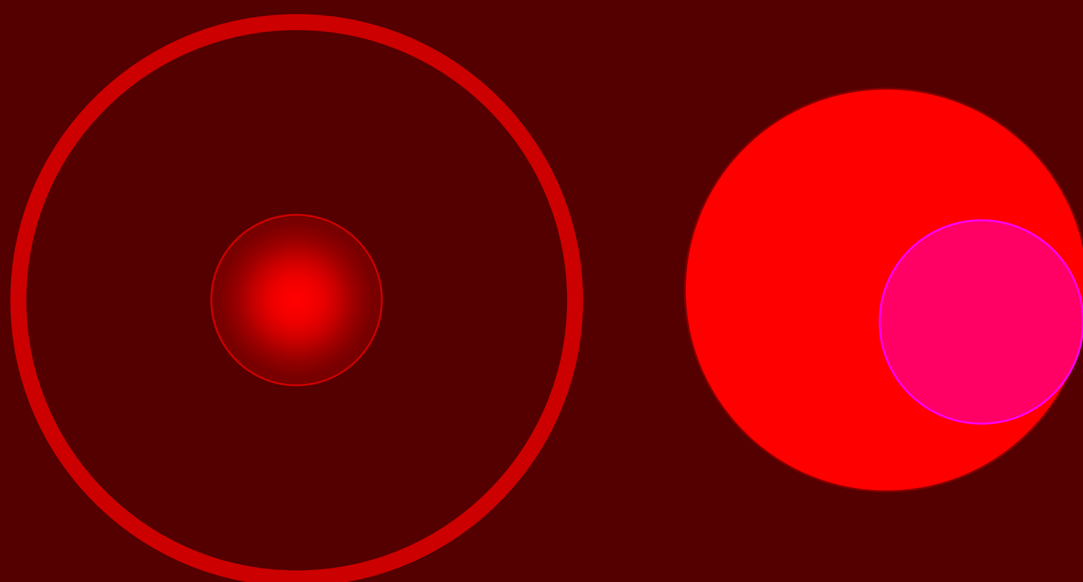
How big is the star?

What is the structure
of the atmosphere?
(Shocks, scattering, etc.)

Are there departures from
spherical symmetry?



My interpretation of the results of the Perrin et al. paper on R Leo



The End!

(or is it the beginning?)